ARCHITECTS AND BOTTLENECKS: ECOSYSTEM ROLES IN THE SOLAR PHOTOVOLTAIC INDUSTRY

INTRODUCTION

Recent research has underscored the importance of ecosystems to a firm's ability to create and capture value (Jacobides, Cennamo, & Gawer, 2018; Kapoor, 2018; Teece, 2014). Ecosystems have been shown to affect which technologies firms choose when entering an industry (Kapoor & Furr, 2015), where firms invest their innovative efforts (Ethiraj, 2007), which strategies firms use to shape the emerging industry (Hannah & Eisenhardt, 2018; Santos & Eisenhardt, 2005) and which firms maintain their advantage as technologies evolve (Adner & Kapoor, 2010, 2016; Furr & Kapoor, 2018). Although this research underscores the importance of the ecosystem to the ability of a focal firm to deliver value to an end user, some significant gaps remain in our understanding of the ecosystem. Specifically, because most research focuses on how the structure of ecosystem interdependence affects focal firms (Adner & Kapoor, 2010; Hannah & Eisenhardt, 2018; Jacobides & Tae, 2015), typically operationalized as the firm making the most representative product in an innovation ecosystem (e.g., cars in the electric car industry, solar modules in the solar photovoltaic (PV) industry, personal computers in the computing industry), we have a limited understanding of how the structure of interdependence in the ecosystem affects the performance of non-focal firms—the providers of components and complements to the focal firm.

To understand how the structure of interdependence affects the performance of all firms in the ecosystem, not just the focal firms, it is important to unpack the different roles firms play in an ecosystem. Prior research suggests that non-focal firms make components or complements that provide value to a focal firm or an end user (Adner & Kapoor, 2010). But some components or complements can play a more important role in the ecosystem than others, depending on their relationship to the ability of the system to function. A component or complement may be a bottleneck that limits the performance of the entire system, thereby elevating its relevance to the ability of the focal firm to create and capture value (Baldwin, 2015; Ethiraj, 2007). Such bottlenecks have been shown to shape the ability of focal firms to create value during industry emergence (Hannah & Eisenhardt, 2018) and to capture value in mature ecosystems (Jacobides & Tae, 2015). Although bottlenecks have been examined in terms of their impact on the focal firm, our understanding of the performance impact on non-focal firms operating in a bottleneck ecosystem element remains limited.

While bottlenecks have featured heavily in the ecosystem discussion, there are additional ways in which non-focal ecosystem participants may influence the final value proposition, beyond simply providing components or complements. One of the most important roles may be that of system architect, specifically those firms that define the architecture for a system, or a part of the system. Analogous to ecosystem engineers in the biological world who modify the pattern of interdependence in a biological system, what sets the architecture role apart is that architects define the relationship of interdependence for the system, or sub-system, thereby establishing who can participation in the ecosystem and setting the boundaries of performance for that system. For example, in the semiconductor industry, whereas silicon producers produce the component input of silicon, lithography equipment manufacturers both provide the component to process that silicon but also define the architecture of the chip making process (e.g., what other components can be used in the process, the size of circuits, the performance of the chip). Although the literature has clearly identified the importance of technology architectures (Baldwin & Clark, 2000), we know less about the performance implications for non-focal firms playing the architect role.

This paper seeks to fill the gap in our understanding by broadening the locus to the entire population of ecosystem participants to explore the performance implications for the different roles non-focal firms may play when contributing to an innovation. We hypothesize that firms participating in a bottleneck ecosystem element have higher survival chances compared to a baseline of firms producing a standard ecosystem element (i.e., non-bottleneck, non-architect). At the same time, not all bottlenecks have an equal impact on the ecosystem, thus we hypothesize that the type of bottleneck a firm occupies affects its survival (i.e., firms occupying a bottleneck created by a *capacity* constraint have lesser advantages than those occupying a bottleneck created by a *control* constraint; Furr et al., 2020). Furthermore, we argue that firms producing architectural ecosystem elements have higher survival chances than firms producing standard elements. However, firms producing upstream architectural elements, because of their potential impact as ecosystem engineers on downstream ecosystem members, will likely have greater survival than those architects at the end of the production chain. Furthermore, we also predict that the survival benefit of architects will be greater than that of bottleneck ecosystem element providers. Penultimately, in the cases where architect and bottleneck roles overlap, we expect these firms will have even greater likelihood of survival. Finally, in a post-hoc analysis, we explore how diversifying or divesting towards bottleneck and architectural ecosystem elements affects firm performance.

We explore these hypotheses on the population of 9,567 firms during the growth phase of the solar PV industry from 2011-2019, just after the resolution of a dominant design and industry shakeout (Agarwal & Tripsas, 2008). Studying this phase of ecosystem evolution is important because it is neither too early, when different ecosystems are competing to be established (Kapoor & Furr, 2015) nor too late, after ecosystem structures have ossified

(Jacobides & Tae, 2015). Instead we can examine how the future dominant ecosystem comes together by observing the entire population of the ecosystem as bottlenecks emerge and resolve.

The analysis yields several observations. First, we note a previously unobserved pattern in the data: although the population of focal firms (solar PV module manufacturers) appears to contract after the emergence of a dominant design consistent with prior research on industry life cycles (Agarwal & Tripsas, 2008; Suárez & Utterback, 1995), the larger ecosystem around these firms actually expands dramatically from about 3,650 firms at the beginning of 2011 to its highest level at the end of 2015 (more than 5,600 firms), before stabilizing around 4,600 firms by 2019. In terms of hypotheses, we find that firms producing a bottleneck had higher survival rates than firms producing standard ecosystem elements and firms playing in a control bottleneck had higher survival benefits than those playing in a capacity bottleneck. Likewise, firms producing an architectural element had higher survival than those producing standard elements, but firms producing upstream architectural elements had the most robust survival among all architects. We also find support that firms producing an architectural element will have greater survival benefit compared to bottleneck players. Finally, firms that produced hybrid ecosystem elements—playing both a bottleneck and architectural role—had the highest likelihood of survival, among the specific roles. The post-hoc analysis supports our prediction that firms that diversified into a bottleneck or architectural ecosystem element had greater survival than those that did not.

These findings make several potential contributions to the literature. First, the observation that the ecosystem expands and then stabilizes while the focal industry contracts following the emergence of a dominant design adds richness to the familiar pattern of industry emergence (Agarwal & Tripsas, 2008; Suárez & Utterback, 1995) and suggests different ecosystem lifecycle dynamics that merit further study. Second, although the literature on ecosystems has expanded the focus from firms at the center of a value chain to consider the role of components and complements contributing to the focal firm's offering (Adner & Kapoor, 2010; Jacobides et al., 2018), this paper expands the lens even further to examine the performance of non-focal firms and the impact of the roles they play. Finally, although the literature has begun to outline the importance of bottlenecks (Ethiraj, 2007; Hannah & Eisenhardt, 2018; Jacobides & Tae, 2015; Kapoor, 2018), this paper provides empirical validation of the survival benefits of participating in a bottleneck ecosystem element but also introduces another important role, discussed in prior literature (Baldwin & Clark, 2000) but not examined at the level of the ecosystem, namely the architects of the ecosystem.

LITERATURE REVIEW AND HYPOTHESES

The study of innovation ecosystems examines how interdependence among firms impacts their ability to create and capture value (Adner, 2017; Adner & Kapoor, 2010; Furr & Kapoor, 2018; Jacobides et al., 2018). This research has broadened the locus of strategy beyond a focus on the firm as an independent actor, or even at the center of a supply chain composed for contractual relationships, to how the firm's position in a structure of formal and informal interdependence shapes almost every firm action, including which technologies firms commercialize upon entering an industry (Kapoor & Furr, 2015), the boundaries of the industry (Santos & Eisenhardt, 2005), the allocation of innovative effort (Ethiraj, 2007); and most importantly, if the industry successfully emerges (Ozcan & Santos, 2015) and which firms prosper as the industry matures (Adner & Kapoor, 2010; Bremner & Eisenhardt, 2019; Furr & Kapoor, 2018; Hannah & Eisenhardt, 2018). But despite the expanding body of evidence about the impact of the ecosystem on firm strategy, most of this research takes the perspective of a focal firm, at the center of an ecosystem, negotiating the relationship with upstream components and downstream complements. Typically, focal firms are operationalized in terms of the most visible, representative, or largest value element in the ecosystem, such as the electric vehicle in an electric vehicle ecosystem or the personal computer at the center of a computing ecosystem. Even when ecosystem studies examine a different ecosystem element, such as the lithography equipment manufacturers in the microprocessor ecosystem, this firm typically “substitutes” as the focal firm in an analysis. Although this tractable approach has yielded many valuable insights, by focusing on how the structure of interdependence affects focal firms, we have a less robust understanding of the simultaneous impact of that structure of interdependence on the non-focal firms, essential to the functioning of a healthy ecosystem.

To explore the impact of the structure of interdependence on all firms in an ecosystem, it is critical to first unpack the many roles firms may take in the ecosystem. The most common model conceptualizes the ecosystem as a fishbone structure, with the backbone of the ecosystem—or what is commonly called the value chain of the industry—being fed by the ribs of the fishbone, which may be upstream components that feed into the focal firm’s production or downstream complements required by the value proposition to the end user (Jacobides et al., 2018; Jacobides, Knudsen, & Augier, 2006; Kapoor, 2018). However, although firms may make components or complements to a focal value proposition, not all components or complements are equally important to the focal firm or to delivering value to end users. It is important to understand how these ecosystem elements (i.e., components or complements) may differ from one another to fully understand how they impact the performance of non-focal firms in an innovation ecosystem.

Bottlenecks

Some firms produce components or complements that are a constraint, or bottleneck, to the performance of the system as a whole (Baldwin, 2019; Kapoor, 2018). Like a bridge can become a bottleneck to the flow of traffic in a road system, an ecosystem element that constrains the ability of firms to create and capture value, acts as a bottleneck to the ecosystem. Bottleneck ecosystem elements can arise at many points in the ecosystem, for example upstream in components as occurred in the PC industry (Ethiraj, 2007) or downstream in complements, as has occurred as the electric car industry has been constrained by limited charging stations (Furr et al., 2020). Bottlenecks have been shown to shape the allocation of innovative effort (Ethiraj, 2007); the ability of the firm to compete (Bremner & Eisenhardt, 2019) and even their ability to profit within an industry segment (Jacobides & Tae, 2015).

Although bottlenecks are often thought of in terms of their impact on the focal firm, namely as a constraint or enabler to the focal firm's ability to create and capture value, the bottleneck also impacts the performance of a non-focal firm producing that ecosystem element. Prior research has established that profits tend to accumulate in segments of an industry that are a bottleneck to the performance of the system (Jacobides & Tae, 2015; Kapoor, 2018). There are several reasons why the non-focal firms producing a bottleneck ecosystem element may have performance advantages compared to firms making standard ecosystem elements. First, when a firm operates in an ecosystem element that is a constraint to the whole, that firm may have more bargaining power over suppliers and buyers, giving them a performance advantage relative to firms producing standard ecosystem elements (Porter, 1980). Second, often demand exceeds supply for bottleneck ecosystem elements, whether that be for the ecosystem element itself or the constraining dimension of performance, increasing the ability of firms producing bottleneck ecosystem elements to extract performance advantages relative to firms producing standard ecosystem elements. Finally, firms occupying a bottleneck ecosystem element, the poor performance of which would threaten the performance of other players in the ecosystem, are more likely to receive support from other ecosystem players to sustain their performance. For example, Ethiraj (2007) found that focal firms sometimes invested in activities that were not their own if it helped to relieve the bottleneck to the use of their own ecosystem elements. Thus, we hypothesize that:

Hypothesis 1 (H1): *Firms who supply a bottleneck ecosystem element have a higher likelihood of survival than firms producing a standard ecosystem element.*

At the same time, recent work suggests there are different types of bottlenecks in an ecosystem. Furr and colleagues (2020) argue for at least three classes of bottlenecks: *technology bottlenecks*, which occur when an ecosystem element is not yet "good enough" in terms of price/performance for a market segment; *capacity bottlenecks* that occur when the element is "good enough" but there is not yet "enough of good enough," and *control bottlenecks*, which ensue when a firm has disproportionate influence over an ecosystem element that causes a constraint in the ecosystem. There may be important differences between a capacity and a control bottleneck, which lead to performance differences among firms producing these different bottleneck types.

A capacity bottleneck occurs when the ecosystem element has adequate performance to satisfy a market niche "is good enough," but because of coordination and investment problems, not enough has been produced (Furr et al., 2020). For example, Furr and Kapoor (2018) described how a capacity bottleneck occurred in the early solar PV industry when there was not enough polysilicon to meet the demand for solar modules. Because of the mismatch between supply and demand, polysilicon producers reaped extra profits. At the same time, although a capacity bottleneck creates a constraint on the ecosystem due to limited supply, the "strength" of this bottleneck, in terms of the sustained impact on a firm's performance, may be limited compared to other bottlenecks. Specifically, although a capacity bottleneck may lead to elevated profits for firms producing these ecosystem elements, if there is a market where these elements are fluidly traded, firms can get access to the components, just at a higher price. Furthermore, if there are few barriers to imitation, or the component can be substituted, competitors will increase supply in response to elevated prices or firms will substitute the constrained component, creating a limit on the durability of increased pricing power. In the case described by Furr and Kapoor (2018), polysilicon suppliers eventually increased supply by building factors and the bottleneck eventually resolved.

By contrast, a control bottleneck arises from appropriation problems rooted in ownership and influence, which are harder to circumvent (Baldwin & Clark, 2000; Teece, 1986). For example, during the emergence of the PV industry, DuPont owned a patent on the material used to encapsulate a PV module to protect it from the weather; this “control” bottleneck allowed them to charge higher prices and constrained the ecosystem (Furr et al., 2020). But competitors could not simply produce more of the bottleneck component because DuPont controlled the intellectual property. One difference between a capacity and control bottleneck is therefore that while a fluid market may exist for capacity bottleneck ecosystem element, but with elevated prices due to the supply constraint, when a firm exercises ownership rights over an ecosystem element, they may control the market for that product, giving them greater power over supply and pricing. Moreover, if firms occupying a control bottleneck have ownership rights that create barriers to substitution, the performance impact for firms occupying this bottleneck will also be more durable than a capacity bottleneck where substitutes exist. The result is that control bottlenecks likely have greater, more durable effect on the performance of firms than capacity bottlenecks. Thus, we predict that firms occupying a control bottleneck will have even greater performance benefits than firms occupying a capacity bottleneck.

> **Hypothesis 2 (H2):** *Firms who produce a control bottleneck ecosystem element will have greater likelihood of survival than firms producing a capacity bottleneck ecosystem element.*

Architects

In the biological ecosystems, certain species, such as a beaver damming a stream, are classified as ecosystem engineers for the substantial impact they have in creating the conditions that affect many other species (Wright, Jones, & Flecker, 2002). Similarly, in innovation ecosystems, certain firms play an ecosystem engineer role by defining the architecture of some part of the system. Baldwin (2015) argues that the architecture of a system "defines its components, describes interfaces between components, and specifies ways of testing performance." Whereas all firms produce components or complements that affect other participants in some ways, like ecosystem engineers in biological systems, firms defining the structure of interdependence of some part of the system create the conditions that affect many other firms in the ecosystem. Drawing on the example of computer manufacturing, both silicon and lithography equipment supply components for chip manufacturing, but lithography equipment suppliers are also architects that define the interdependence of multiple elements such as which power sources, lenses, and resists can be used, how they can be used (e.g., under water or not), and what kinds of products can be made with them. The result of defining the structure of interdependence is that architects typically define the right to participate and the boundaries of performance for other firms in the ecosystem, which is a different role from simply producing a component or complement.

Moreover, the architect role is different from the bottleneck role in the sense that while bottlenecks create a direct constraint to performance (i.e., not enough silicon creates a bottleneck to producing modules), architects create an indirect constraint to performance (i.e., setting the structure of interdependence affects which firms can participate in the ecosystem and the performance they can achieve with the architecture). As a result, although it is possible that in some situations an architecture that is not "good enough" also becomes a bottleneck because the architecture is the limiting factor to system performance, the defining feature of an architecture is not constraining performance but in setting the structure of interdependence. For example, in the personal computer (PC) ecosystem, the system bus, which defines which components can be used in the PC and how they interface is not typically a bottleneck, although at points in the evolution of PCs the architecture became insufficient and had to be redesigned (Chesbrough, 2003).

Firms can play the role of architect at different levels of the technology stack, setting architectures within modules, sub-systems, or the system as a whole (Murmann & Frenken, 2006), and thus there can be many firms playing an architectural role within an innovation ecosystem. As a result, architectural elements may be upstream or downstream from a focal firm. Upstream architects are component suppliers that determine the architecture of a component, module, or subsystem downstream that shapes the focal firm's ability to create value. For example, solar PV capital equipment manufacturers determine the architecture of downstream solar cell manufacturing, including which components can be used in the process and which product features can be produced (e.g., thickness, polishing, texturing, etc.). As a result, they define the structure of interdependence for the solar cell manufacturing activity in a way that indirectly constrains the system by defining who participates and the boundaries of performance for that subsystem. Architects may also be downstream complement suppliers that determine the architecture of the system delivered to an end consumer. In this role, architects define the structure of interdependence, which determines who participates and the performance of the innovation adopted by an end user. For example, in the solar PV industry, installers determine the architecture of the final power generating system by selecting components and complements and then combining them, in relation to the specific environment (e.g., axis, tilt, shade, etc.), which then determines the performance of the system.

There may be several advantages (and disadvantages) to playing an architectural role in an ecosystem. To begin with the disadvantages, designing an architecture comes with costs and if one or few firms are responsible for designing an architecture, they bear those costs as part of delivering an innovation. Moreover, architectures often require coordination with the ecosystem to ensure the interfaces with the architecture are mutually acceptable and that coordination introduces another potential cost. Finally, architectures are often contested, and the competition to establish an architecture as dominant can introduce further costs. Technology histories are indeed replete with the stories of costly competition between technology standards, such as QWERTY or VHS (Arthur, 1989; Cusumano et al., 1992), between technology variants during the era of ferment (Abernathy & Utterback, 1978; Agarwal & Tripsas, 2008; Utterback, 1994), or of the failure of an ecosystem to emerge due to competition between participants (Ozcan & Santos, 2015). Thus, playing the role of architect in an ecosystem does not come without costs.

But while there may be costs of playing an architectural role, there are also benefits. First, because architects define relationships and performance boundaries for others, firms dependent on the architects may be willing to pay higher prices if the new architecture gives them a performance advantage in the industry. For example, in the solar PV industry, advances in wafer slicing machinery towards ever thinner crystalline silicon (cSi) wafers increased the performance of many downstream players, thus raising the willingness of these downstream players to pay higher prices for their products. Second, if architects invest in R&D or embed knowledge in architectures, they may create knowledge spillovers downstream that shape the allocation of value in the ecosystem. In support of this argument, Hoppmann (2018) found evidence that solar PV module manufacturers benefited from knowledge spillovers from equipment manufacturers into their own operations. Third, because the architect defines the components that interoperate with the architecture, the architect may have significant power over their suppliers who run the risk of being excluded from an architecture (Porter, 1980) or over buyers for whom adopting a new architecture would impose switching costs, thus allowing architects an advantageous position affecting their performance. For example, in the solar PV industry, installers of PV systems decide which modules, inverters, and other elements they combine to create a working PV system and thus have power over their suppliers. Finally, if architects accrue architectural knowledge over time, which allows them to increase the performance of the system given a fixed set of inputs (Baldwin, 2019; Furr & Kapoor, 2018; Helfat & Campo-Rembado, 2016), they may capture further value from system delivery. For example, beyond selecting components, the accumulated architectural knowledge of how to design more productive PV systems makes solar PV installers more valuable to the ecosystem than the value of the components alone. For these reasons, we hypothesize that:

> **Hypothesis 3 (H3):** *Firms who produce an architectural ecosystem element have higher likelihood of survival than firms producing a standard ecosystem element.*

At the same time, just as there are differences between bottlenecks, there are potential differences between architects. Some architects, particularly those upstream, both impact the firms upstream from them (by defining which elements can be part of the architecture) but also have a cascading impact on firms below them. Just as woodpeckers engineer the ecosystem by creating holes in trees that serve as shelter for smaller animals, which in turn both create and consume food for other species, upstream architects engineer the ecosystem in a way that affects many firms below them. In the example of solar PV wafer slicing equipment, thinner wafers decreases the costs of cells, as well as modules, as well as the final system, allowing more power to be generated per dollar, thereby making the entire system more attractive and PV more tenable as a substitute for grid electricity. These cascading benefits can come from relieving a performance constraint, R&D spillovers (Hoppmann, 2018), enabling new features, or other such benefits. Arguably, the longer the chain of downstream dependence, or the greater the ripple of an architect's actions on the ability of other firms to create and capture value, the greater the likely performance of that firm.

By contrast, for downstream architects, the chain of downstream dependence is much shorter. Downstream architects are also engineers in the sense that they have power over which components and complements to integrate into a system, as well as set the performance of the final system adopted by end user, which allows these firms to access many of the architect role advantages described above. However, because the chain of downstream dependence benefits (e.g., performance, R&D spillover, new features) is shorter, their ability to capture value from the ecosystem may be more limited, simply because there are fewer firms dependent on them downstream. Unless the downstream architect can find other ways to increase the dependence of end users on their role (e.g., Apple's system design and marketing), we hypothesize that the performance benefits for upstream architects will be greater than for downstream architects.

Hypothesis 4 (H4): *Firms who produce an upstream architectural ecosystem element will have greater likelihood of survival than firms producing a downstream architectural ecosystem element.*

Bottlenecks versus Architects

Although producing a bottleneck ecosystem element has advantages, one dilemma firms face is that bottlenecks evolve over time. Bottlenecks may evolve in terms of the type of constraint they represent, for example from technology to capacity constraints (Furr et al., 2020; Madsen et al., 2019), or from one part of the ecosystem to another (Hannah & Eisenhardt, 2018). Thus, although a firm may benefit from producing a bottleneck ecosystem element while it is a bottleneck, if that bottleneck resolves, the survival benefits associated with that part of the ecosystem may fade. In contrast to bottlenecks, architectures may be more durable within a given technology generation (although notably architectures are often overturned between technology generations). The reason that architectures tend to be more durable than bottlenecks is that once an architecture is established within a given technology generation, there are significant costs associated with changing architectures. Firms develop products that are interdependent with an architectural configuration, as well as related knowledge about the architecture, which creates a switching cost thereby making architectures more durable. Furthermore, if there are regulations associated with the product, changing architecture often requires requalifying the product with regulators. In addition, if customers have complements or activities interdependent with the architecture (e.g., software interdependent with an operating system), that also introduces a switching cost. The challenges of switching architectures have been a major source of inertia for firms adapting to technology changes (Henderson & Clark, 1990; Tripsas, 1997). As a result, architectures tend to change less quickly, often only between technology generations, compared to bottlenecks, which can emerge and resolve in many places in the ecosystem during a single generation. For this reason, we hypothesize as follow:

> **Hypothesis 5 (H5):** *Firms who produce an architectural ecosystem element will have greater likelihood of survival than firms producing a bottleneck ecosystem element.*

Hybrids: Bottlenecks and Architects

Despite the differences between the role of producing an ecosystem element, which may or may not be a bottleneck, and the architectural role, which adds the activity of defining the structure of interdependence, it is possible that there are times that an architectural role also becomes a bottleneck. This can occur when the boundaries of performance set by the architecture also becomes a constraint or when the supply of firms playing an architectural role is constrained. In the situation where the architectural firm also becomes a constraint, the advantages of occupying a architectural position in the ecosystem—namely, the performance benefits of determining which components are included in a system, defining the boundaries of performance for other firms, and capturing more value related to architectural knowledge—are likely only complemented by the survival benefits of producing a bottleneck ecosystem component. Thus, we hypothesize that system architects have greater survival benefit when they produce an ecosystem element that is both an architecture and a bottleneck.

> **Hypothesis 6 (H6):** *Firms who produce an architectural ecosystem element that is also a bottleneck ecosystem element have higher likelihood of survival than producing the same element when it is not a bottleneck.*

RESEARCH CONTEXT

We explore these questions in the context of the solar PV industry after the resolution of a dominant design but before the ossification of industry structure, in the period 2011–2019. The solar PV industry is a rapidly growing member of the renewable energy sector, which experienced considerable growth from less than five gigawatts of installed capacity in 2005 to over 500 gigawatts in 2018 with a market value of $86 billion in 2015 (Statista, 2019). Furthermore, an estimated 1,955 GW of solar PV installations are expected between 2019 and 2028, generating about $2 trillion in revenue globally ("Market Data: Solar PV Country Forecasts," 2019). The increasing societal pressure to move away from fossil fuel has further increased the prominence of the solar PV industry and raises the importance of evaluating successful firm strategies in this context. Beyond the environmental and economic prominence, the solar PV industry is also an ideal setting to study how the role firms play in innovative ecosystems influences their performance because firms in this industry may play several different roles depending on which element of the solar PV ecosystem they produce. By "elements", we refer to both the components of a solar PV module, such as the panel and the materials needed to produce it (e.g., crystalline silicon, cell processing machines, assemblers, etc.), as well as the complements that are needed for a solar PV system that delivers electrical energy for use (e.g., the inverter, the racking or mounting system, installation and sales). Depending on which elements they produce or supply, firms may occupy the roles of upstream or downstream architects; furthermore, depending on the timing, they may be producing or supplying bottleneck elements in the ecosystem. The dynamic and evolving context of the industry allows us to study the implications of playing different roles in an ecosystem on the performance of non-focal firms.

Because the era of ferment represents a period of experimentation in which a rising tide floats many boats, we focus on the period after the emergence of a dominant design during which the industry and the ecosystem evolve and we can focus on the emergence and maturation of a single technology ecosystem rather than many competing ecosystems (Kapoor & Furr, 2015). Specifically, the study captures the population of all firms in the ecosystem from 2011–2019, which allows us to observe the dynamism of competitive moves as ecosystem players adjust to the emergence and resolution of multiple bottlenecks and prepare for the maturation phase of the industry. During this period, we observe highly dynamic and competitive movements between the different roles firms played, changes in the ecosystem elements they produced/supplied, and entry and exit over the entire period. Our study period therefore covers the critical, but rarely studied time period after the emergence of dominant design as the industry begins to coalesce towards a stable, mature ecosystem.

Data

Our main analysis draws on the most comprehensive secondary data source in the solar PV industry, ENF Solar, which is the largest solar trade platform and directory of solar companies. Thus, our sample includes virtually the entire population of firms in the solar PV ecosystem globally between 2011 and 2019. This population consists of 9,567 unique firms from Asia, Europe, North America, Middle East, South America, and Oceania, with the greatest proportion of firms coming from Asia and Europe. The dataset contains information on each company, such as name, location, contact details, firm size as well as the solar system elements the firms produces or supplies quarterly. We have information of firms who were providers of materials, panel, specialized equipment, balance of systems (such as racking, inverters etc.), sales, installation, service and applications in the solar PV ecosystem. Just as importantly, the dataset tracks active participation in the industry and records that a firm exists.

Industry background

The solar photovoltaic effect—or the creation of voltage and electric current in a material when exposed to sunlight—was first observed by French physicist Edmond Becquerel in 1839 and the first solar cells developed by Charles Fritts in 1884. However, the first solar modules, which are a series of solar photovoltaic cells wired in a series to produce electricity, were first developed by Bell Labs in 1955. Although there were several attempts to commercialize solar PV, most notably during the oil crisis in the 1970s, a sustainable industry did not emerge until near the turn of the century, when an increase in entrants in the 1990s and 2000s kicked of an era of ferment, characteristic of new industry emergence (Agarwal & Bayus, 2002; Agarwal & Tripsas, 2008; Suárez & Utterback, 1995). Specifically, during this period, large numbers of both startups and diversifiers entered the industry attempting to commercialize solar modules based on radically different technologies, primarily, crystalline silicon, cadmium telluride, amorphous silicon, and copper-indium-gallium-diselenide combinations (Kapoor & Furr, 2015). In 2008, the first signs emerged to suggest crystalline silicon may become the dominant design and by 2011, an industry shakeout was in full swing, tapering off in 2015 (Furr & Kapoor, 2018). By the end of this period, most firms producing competing technologies exited.

Empirical analysis

Our hypotheses predict survival of firms over a period of industry evolution. Prior studies of industry evolution have employed event history analysis to study firm survival because it has the advantages of accounting for time-variant covariates while also dealing with issues of left and right censoring (Cleves, Gould, Gutierrez, & Marchenko, 2016).

We use accelerated event time regressions to test our hypotheses, where the hazard and survival functions have distinct functional forms (Cleves et al., 2016). This is a necessary assumption because some variables in our models fail the proportionality test, which would be required for a semi-parametric approach. Furthermore, because our data is collected quarterly, tied event times are likely, which further complicates the use of the Cox model. We nevertheless conduct some robustness tests using the semi-parametric estimation, where we attempt to account for some of these challenges. To parametrically model the baseline hazard of firm survival, we use the standard log-logistic model (Blossfeld, Golsch, & Rohwer, 2007) because of its flexibility to estimate both monotonically decreasing transition rates as well as transition rates that monotonically increase at the start up to a maximum, then fall monotonically. Prior literature observing high initial failure rate of firms in nascent industries that declines over time (Carroll & Hannan, 2004) makes the log-logistic distribution appropriate to model firm survival in parametric analysis.

In order to avoid left censoring issues, we restrict our analysis to firms who entered the dataset after the first recorded quarter (i.e. firms who entered in March 2011 or later). Furthermore, we also exclude three firms from the analysis that enter our database for one period with zero number of employees. We define our *failure* as exit from the industry (0 while the firm is present in the ecosystem, turning 1 for the last quarter the firm is active before exiting); firms who are still in the database in the last recorded quarter are considered censored. Recognizing that there might be unobserved heterogeneity among firms, particularly in terms of their resource endowments, we use a shared-frailty model by including an error term with Inverse-Gaussian distribution and assume that the frailty is firm-specific.

Independent variables

The primary independent variables measure if a firm produced an ecosystem component or complement that was a bottleneck element, architectural element, or neither. The dummy variable *bottleneck* equals to 1 when the firm is producing a bottleneck ecosystem element, without playing an architectural role (and zero otherwise), specifically seller or balance of systems. There have been multiple bottlenecks over the emergence of the solar PV industry, including bottlenecks in components such as silicon, solar cells, financing, and so forth. During the period of study, the primary bottlenecks in the solar PV ecosystem, as identified by Hannah and Eisenhardt (2018) were installation, sales, and racking (which we call balance of systems, BoS). Their interviews revealed that with the resolution of component bottlenecks upstream, a significant drop in the cost of solar panel manufacturing led to a glut in the market, which coincided with increased competition among financing firms that led the bottleneck to shift to sales. While the cost of sales remained high for a period, once residential solar became more widespread, customers started seeking out solar firms for bids, which reduced the cost of finding customers and additionally, the bottleneck in sales resolved and shifted to installation and BoS from 2013 onwards. The BoS element underwent technological innovation whereby the time needed to install the solar panels went down considerably; thus, together with installation, racking also became a bottleneck component (Hannah & Eisenhardt, 2018). Given the evolution of bottlenecks uncovered by the qualitative study, we identify BoS as the *capacity bottleneck* (that takes the value of 1 when the firm is a BoS producer and 0 otherwise) in the solar PV industry because firms for a while had problems accessing such complements that were "good enough" for installation. We also identify sales as the *control bottleneck* (that takes the value of 1 when the firm is in sales and zero otherwise) because firms who engaged in sales directly controlled access to customers.

The dummy variable *architect* equals 1 when the firm is producing an architectural ecosystem element, specifically capital equipment or installation (and zero otherwise). In the solar PV industry, capital equipment manufacturers produce a critical upstream complementary asset (Kapoor & Furr, 2015) that determines the boundary of performance for firms downstream producing solar PV (Hoppmann, 2018). Examples include solar wafer slicing equipment (which shapes the thickness of cells and thus their cost), solar cell processing equipment (which shapes the percentage of light converted to electricity and thus productivity), and solar module assembly equipment (which determines the efficiency of production). We identify this ecosystem element as an *architect* element and in the more fine-grained hypothesis as an *upstream architect* (that takes the value of 1 when the firm produces specialized equipment and 0 otherwise) because these firms play a prominent role in the focal firm's ability to create value for customers by engineering the ecosystem "below" them. By contrast, downstream solar system installers are responsible for "installation in the ideal location, sourcing the best quality components, making sure it is safe, and that it delivers a good energy yield" (Shah, 2015). Thus, installers are identified as *architects*, and in the more fine-grained analysis as *downstream architects* of the final system, bringing together components, and executing the design in a way that determines the boundaries of performance of the entire system to the end user. Furthermore, installation also became a bottleneck when the cost of sales has decreased (Hannah & Eisenhardt, 2018); therefore, after 2013, these firms took on the role of *hybrids* (that takes the value of 1 if the firm entered installation in or after 2013 and 0 otherwise).

Beyond bottlenecks and architects, the dummy variable *standard* is equal to 1 when the firm is producing fundamental solar PV components that are non-bottleneck, non-architectural elements (and zero otherwise) such as panel and materials.

Control variables

We also create a set of control variables in the dataset related to firm, industry, and competitive dynamics to control for other factors that may affect firm survival (Furr & Kapoor, 2018). To control for firm *size*, and thus potential factors such as market power, access to resources, and so forth, we use the number of employees as a proxy since actual production numbers are revealed in only a subset of cases. To control for the munificence and competition in the ecosystem, we introduce controls for *ecosystem* size, measured as the number of firms in the entire ecosystem in every quarter. To control for the munificence and competition within a specific ecosystem element, which is effectively a micro-industry, we measure *industry* size as the number of firms in the specific sub-set of the ecosystem elements a given firm is present in. To capture the dynamics of entry that may be affecting ecosystem entry, we introduce the variable *entry* as the count of firms entering the specific sub-set of ecosystem elements a firm is present in, quarterly. In addition to control for the benefits and costs of firm scope, we introduce the variable *scope*, as the count of ecosystem elements in which a firm participates in each quarter. Finally, to control for potential advantages to firms operating in each geography, whether due to regulation or favorable access to resources, we control for the geography of the firm by introducing the variable *continent*.

RESULTS

Figures 1 and 2 illustrate the evolution of the ecosystem as a whole. The most notable observation is that the ecosystem appears to have a different evolutionary pattern than that observed in the more familiar studies of focal firms (e.g., Suárez & Utterback, 1995). Specifically, in most studies of industry evolution of focal firms, entry rises during the era of ferment, peaks at the emergence of the dominant design, and is followed by a period of industry population decline as the industry stabilizes. Although this pattern clearly held for the focal firms in the solar PV industry, where entry peaked in 2008 and then, following the emergence of a dominant design, an industry shakeout starting in 2010 led to a dramatic decline through 2015 (Furr & Kapoor, 2018); in the larger ecosystem, there appears to be a dramatic expansion from the 2010 period onward (Figure 1), which appears particularly stable in the non-focal ecosystem firms (Figure 2). The patterns suggest a proposition that although the emergence of a dominant design leads to shakeout for focal firms, the burst in consumption released by the dominant design leads to an expansion and stabilization of the larger ecosystem at the same time.

In terms of the statistical analysis, Tables 1 and 2 present the descriptive statistics and correlations for the variables utilized in the analysis. Table 3 reports the results of the accelerated event time regressions. Model 1 is a baseline model with control variables only. Model 2 adds the *bottleneck*, *architect* and *standard* variables. Model 3 expands Model 2 to explore the survival implications of firms playing different bottleneck and architectural roles in the ecosystem by replacing the measures of bottleneck and architect with fine-grained measures of bottlenecks (i.e., *capacity* vs *control bottleneck*) and architects (*upstream* vs *downstream architect*). Model 4 assesses the survival implication of producing a hybrid architectural and bottleneck element by restricting the sample to only those firms who were ever installers.

Hypothesis 1 argued that firms participating in a bottleneck ecosystem element would have a higher likelihood of survival than those producing a standard element. The coefficient for *bottleneck* in Model 2 is positive and significant providing support (chi2 = 7.22, p = .0271). Furthermore, the positive and significant coefficient for *control bottleneck* compared to the insignificant *capacity bottleneck* coefficient in Model 3 provides support for Hypothesis 2 and underscore the importance of understanding the performance implications for the different roles (even within "established" roles such as bottleneck) firms play in innovation ecosystems.

Hypothesis 3 argued that firms participating in an architectural ecosystem element would have a higher likelihood of survival than those producing standard elements. The positive and significant coefficient for *architect* in Model 2 supports the hypothesis (chi2 = 15.49, p = .0004). Model 3 also provides support for Hypothesis 4 that predicted higher survival benefits for upstream architects, which has a positive and significant coefficient compared to downstream architects, a role that provides no significant benefit to firms according to our analysis (chi2 = 11.16, p = .0038).

Hypothesis 5 predicted that the survival benefit to architects will be greater than those to bottlenecks. The significant difference between the coefficients associated with *bottleneck* and *architect* in Model 2 lends support for this hypothesis (chi 2 = 15.45, p = .0004). We further compared the survival benefit of *control bottlenecks* to *downstream architects* and the significant difference between the associated coefficients (chi2 = 11.46, p = .0033) provides further support for the hypothesis.

Hypothesis 6 argued that firms producing an architectural ecosystem element when it is a bottleneck have a higher chance of survival than if firms are present in this element when it is not a bottleneck. The positive and significant coefficient for *hybrid* in Model 4 provides support for Hypothesis 6. Our analysis also supports highest survival benefit for hybrid players among the specific, fine-grained roles in innovation ecosystems.

To ensure robustness, we tested the fit of our chosen distribution with the Akaike Information Criterion (Akaike 1974) and find that the log-logistic distribution has the best fit alongside with the generalized gamma distribution. We test our models using this alternative distribution, used in some previous works (Bercovitz & Mitchell, 2007) and find that our results are robust to this alternative specification without the inclusion of the frailty term. Similarly to other works using parametric survival analysis (Pe'er, Vertinsky, & Keil, 2016), we conduct further robustness checks by estimating our bottleneck and architect variable coefficients using the Cox proprotional hazard model and testing the proportionality assumption using Schoenfeld residuals. Our results are also robust to this semi-parametric approach, operationalized with exact marginal-likelihood method to handle tied failures ("exactm" option in Stata). We report our Cox regression results for our main analysis in Table 4.

Post-hoc analysis

All ecosystems have an evolutionary element in the sense that bottlenecks emerge and resolve over the course of an industry. While it is true that architectural roles can evolve (e.g., Intel redefining the motherboard module around their own chip), architectural roles may be more stable than bottlenecks which arise and resolve multiple times over the course of an industry (Ethiraj, 2007). Thus, firms may need to be particularly reactive to the emergence and resolution of bottlenecks. Although there may be greater benefits to participating in a bottleneck ecosystem element, because bottlenecks evolve with the evolution of the industry (Furr et al., 2020), what is the best strategy for finding and participating in a bottleneck? Hannah and Eisenhardt (2018) conducted a qualitative study of the residential installation segment of the PV value chain and observed firms choosing different strategies, drawing a contrast between firms that choose to play in a single component and firms playing in multiple components at once. Although observed only in a multi-case study, the authors conclude there are survival benefits to a dynamic strategy that responds to bottlenecks. If a firm has the foresight or luck to enter a component that becomes a bottleneck, they will likely have a higher likelihood of survival than if they enter in a non-bottleneck component. But what happens to the firm that does not enter a bottleneck component, or that has entered multiple components, only one of which ends up being a bottleneck? Do the benefits outweigh the costs of a more dynamic strategy of changing which components a firm plays in? And which is the best strategy?

One strategy firms may choose is to enter a component, and then, upon discovering that a bottleneck has evolved elsewhere in the ecosystem, to diversify into the ecosystem element that is a bottleneck. Such a strategy has costs and benefits. Entering a new ecosystem element requires the acquisition of new technology and operational capabilities and exposes the firm to the competition and liabilities of newness associated with a new activity (Stinchcombe, 1965). However, because the firm already operates in the ecosystem, they may have transferable knowledge, including integrative knowledge (Furr & Kapoor, 2018; Helfat & Campo-Rembado, 2016; Moeen, 2017), as well as other assets (e.g., brand recognition, distribution networks, etc.) that lower these costs relative to outsiders to the industry. We therefore predict that firms who diversify from non-bottleneck ecosystem elements into bottleneck ecosystem elements have a higher likelihood of survival than firms that do not change the number of elements they operate in.

A second strategy firms may employ is to enter multiple ecosystem elements at once, and upon the discovery that one element has become a bottleneck, to divest the non-bottleneck ecosystem elements. A divestiture strategy has costs, including the loss of seemingly unrelated capabilities that in fact have an underlying relatedness (Feldman, 2014). It also has risks, namely that the firm divests to focus on a bottleneck and then the bottleneck resolves. But such a strategy also has benefits. Divestiture frees up resources from less productive activities that can be reinvested into the bottleneck ecosystem element, increasing the firm's ability to take advantage of the bottleneck. The benefits of focus come both from the application of greater resources to the opportunity with higher payoffs and from the reduction of the demands of scope on non-scale free resources that limit growth (Levinthal & Wu, 2010). Given the potential benefits to focusing the firms' resources on the bottleneck, namely increased profit, decreased substitutability, and greater ecosystem support, we expect that firms who divest non-bottleneck ecosystem elements to focus on bottleneck ecosystem elements have a higher likelihood of survival than firms that do not change the number of elements they operate in.

To test our predictions about dynamic firm strategy, we create a dummy variable, *diversify*, equal to 1 for firms who have diversified into a bottleneck (BoS[1]) element. We also create a dummy variable, *divest*, variable for firms who have divested non-bottleneck elements i.e. panel and material. Finally, for comparative purposes, we create a dummy variable, *no change*, which equals to 1 for firms who played in the same number of elements through their entire history in the solar PV industry.

We report our post-hoc analysis results in Tables 5 and 6, using both accelerated failure time regressions as well as Cox semi-parametric estimations. For the semi-parametric models we include variables that fail the proprotionality test (*diversify*, *no change*) as time-varying covariates (Blossfeld et al., 2007). We find that there is a statistically significant survival benefit to diversifying into a bottleneck compared to not changing the number of elements a firm ever played in (chi2 = 29.03, $p < .0000$, when comparing coefficients from the accelerated failure time regressions). By contrast, we find a statistically significant survival punishment for divesting away from standard components compared to remaining in the same components over time (chi2 = 46.05, $p < .0000$, when comparing coefficients from the accelerated failure time regressions).

DISCUSSION AND CONCLUSION

Ecosystems play a central role in the ability of firms to create and capture value as new industries emerge (Adner and Kapoor 2010; Jacobides et al. 2018; Kapoor, 2018). Although

[1] We used only BoS for this variable to focus on the impact of diversifying into a bottleneck (rather than into a hybrid element) and to capture all potential entry, which is not possible for sales given it was already evolving as a bottleneck at the start of our data collection period.

prior research has emphasized the role of ecosystem components and complements on critical strategic choices for focal firms, the supporting actors in the ecosystem—the non-focal firms—are rarely studied. As a result, although we have a robust picture of how focal firms are affected by interdependencies in the ecosystem, we have a limited picture of the implications for non-focal firms occupying those interdependencies.

In this paper, we examine how non-focal firms’ choices to produce ecosystem components or complements with different characteristics affect their survival during a dynamic period of ecosystem evolution. The results provide pertinent insights into how ecosystems composed of non-focal firms merge differently and similarly from the picture developed by studying focal firms. Firstly, by leveraging a comprehensive dataset of the solar industry representing the entire population of the ecosystem, we observed that the pattern of ecosystem emergence did not follow the same evolutionary pattern as that for focal firms. Although the emergence of the dominant design was leading to a contraction of the number of focal firms (Furr & Kapoor, 2018) consistent with the dominant pattern of industry evolution (Agarwal & Tripsas, 2008; Suárez & Utterback, 1995), the larger ecosystem was expanding and then stabilizing, particularly among the primary ecosystem element categories. This observation suggests the opportunity to examine the ways in which the lifecycle of ecosystems matches or diverges from that of focal firms. We proposed that the expansion of the ecosystem could be due to the very fact that the dominant design unleashes demand for the focal product by arriving at a price/performance design compromise (Anderson & Tushman, 1990) that expands the market, even if it leads to consolidation for focal firms after an era of ferment. However, this requires further research.

Second, the results suggest that there are distinct survival benefits for playing different roles in the ecosystem. Prior research has underscored the importance of bottlenecks in the evolution of an ecosystem (Ethiraj, 2007; Hannah & Eisenhardt, 2018; Jacobides & Tae, 2015; Kapoor, 2018) as well as the role of architectures in the development of technical systems (Baldwin & Clark, 2000). We find that firms playing bottleneck and architectural roles have greater survival benefits than those producing standard components and firms producing an element that was both a bottleneck and architectural ecosystem element had the highest likelihood of survival among the specific roles. But just as importantly, we explore differences in the types of bottlenecks and architectural roles firms can play. The results suggested that firms occupying control bottlenecks appeared to have greater performance than firms occupying capacity bottlenecks. Likewise, firms playing an upstream architectural role had more robust likelihood of survival than firms playing a downstream architectural role. We further show that the survival benefit of bottleneck element providers is less than the benefit of players who can influence the structure of interdependence in the ecosystem, i.e., architects. These results provide evidence for the benefits of expanding our view of ecosystems to pay closer attention to the different roles firms play, beyond component or complement producer. In this paper we provide evidence for differences between bottlenecks suggested by prior work (Furr et al., 2020) and introduce new roles, such as ecosystem engineer, which can have a profound impact on the evolution and performance of an ecosytem.

Lastly, the post-hoc analysis provides initial clues into the importance of a dynamic approach to studying ecosystem strategy. Although research frequently looks at strategy choices in binary terms to enable emprical tractability (e.g., firms either chose technology A or technology B), the study tried to introduce a more dynamic perspective to ecosystem strategy. As bottlenecks evolve with ecosystem emergence and as firm capabiltiies evolve with firm participation in the ecosystem, firms may frequently choose to navigate to or from different parts of the ecosystem. The results suggest benefits to diversifying into bottleneck ecosystem elements or diversfying away from non-bottleneck ecosystem elements, a more dyanmic view of ecosystem strategy (see Hannah & Eisenhardt 2018) that offers rich territory for future research.

Notably the study has several important limitations that suggest important boundary conditions to these observations. First, the strength of the study is a focus on the post era-of-ferment stage of the industry, a period rarely studied, with a dataset that includes all firms participating in the ecosystem. But the limitation of the study is that reliable data is only after the era of ferment. Furthermore, as a contemporary study, the future of the industry is still to be determined, introducing right-censoring as the industry has yet to fully mature. In addition, modeling the evolution of firms, who may participate in different parts of an ecosystem at different times, presents significant challenges. In this study, we chose to simplify the analysis by indicating participation when the firm is present in a given ecosystem element (by quarter). This means that our capacity and control bottleneck variables indicate whether the firm is in one of those elements in a given quarter, except for when we are assessing survival benefits of hybrid players, which is restricted to a specific period of time (after 2013). Finally, like all studies, there are limitations to the availability of data and there may always be factors we have been unable to account for, which also influence survival. Given these limitations, we hope these results encourage the study of ecosystem dynamics and of all firms in the ecosystem, both focal and non-focal firms.

TABLES

TABLE 1. Summary of variables

Variable	Obs	Mean	Std.Dev.	Min	Max
Failure	95,491	0.0281	0.165	0	1
Size	95,491	147.7	217.7	1	734
Ecosystem	95,491	5066	312.7	3836	5674
Industry	95,491	2194	1148	78	7104
Entry	95,491	76.11	107.0	0	1580
Continent	95,491	1.426	0.720	0	3
Scope	95,491	1.261	0.556	1	8
Bottleneck (Seller/ BoS)	95,491	0.256	0.436	0	1
Architect (Equipment / Installer)	95,491	0.664	0.472	0	1
Standard (Panel / Material)	95,491	0.213	0.410	0	1
Upstream Architect (Equipment)	95,491	0.0479	0.214	0	1
Downstream Architect (Installer)	95,491	0.616	0.486	0	1
Control Bottleneck (Seller)	95,491	0.135	0.342	0	1
Capacity Bottleneck (BoS)	95,491	0.135	0.342	0	1
Hybrid	95,491	0.662	0.473	0	1
Diversify	95,491	0.00925	0.0957	0	1
NoChange	95,491	0.841	0.365	0	1
Divest	95,491	0.0974	0.297	0	1

TABLE 2. Correlation matrix

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
Failure	1.00																	
Size	-0.01***	1.00																
Ecosystem	-0.01***	-0.01	1.00															
Industry	-0.02***	-0.32***	0.06***	1.00														
Entry	-0.01	-0.14***	0.06***	0.38***	1.00													
Continent	-0.00	-0.16***	0.07***	0.15***	0.05***	1.00												
Scope	0.01***	0.06***	-0.04***	0.32***	0.15***	-0.12***	1.00											
Bottleneck (Seller/ BoS)	0.01***	0.03***	0.01*	-0.09***	0.01*	-0.06***	0.45***	1.00										
Architect (Equipment / Installer)	-0.03***	-0.35***	-0.00	0.80***	0.32***	0.18***	-0.03***	-0.30***	1.00									
Standard (Panel / Material)	0.02***	0.34***	-0.01**	-0.35***	-0.14***	-0.18***	0.34***	-0.14***	-0.59***	1.00								
Upstream Architect (Equipment)	-0.00	0.10***	0.00	-0.33***	-0.13***	-0.06***	-0.05***	-0.11***	0.16***	-0.08***	1.00							
Downstream Architect (Installer)	-0.03***	-0.38***	-0.01	0.93***	0.37***	0.20***	-0.00	-0.24***	0.90***	-0.53***	-0.28***	1.00						
Control Bottleneck (Seller)	0.01*	-0.15***	0.03***	0.18***	0.12***	0.01*	0.45***	0.67***	0.00	-0.14***	-0.09***	0.04***	1.00					
Capacity Bottleneck (BoS)	0.01**	0.17***	-0.03***	-0.25***	-0.09***	-0.08***	0.26***	0.67***	-0.39***	-0.03***	-0.06***	-0.35***	-0.03***	1.00				
Hybrid	-0.01**	0.22***	-0.10***	-0.47***	-0.34***	-0.32***	-0.04***	0.09***	-0.46***	0.27***	0.15***	-0.52***	-0.05***	0.16***	1.00			
Diversify	-0.01**	0.06***	0.00	0.02***	0.01*	-0.01**	0.15***	0.03***	-0.03***	0.13***	-0.01	-0.03***	-0.02***	0.07***	-0.03***	1.00		
NoChange	0.00	-0.09***	-0.03***	0.03***	-0.01*	0.09***	-0.35***	-0.16***	0.18***	-0.26***	0.06***	0.15***	-0.15***	-0.10***	0.04***	-0.13***	1.00	
Divest	-0.00	-0.05***	-0.00	0.11***	0.03***	0.03***	-0.05***	-0.03***	0.11***	-0.12***	-0.07***	0.14***	-0.12***	0.07***	-0.10***	-0.01*	-0.11***	1.00

TABLE 3. Accelerated failure time estimates (using Inverse-Gaussian shared frailty) based on different ecosystem roles of solar PV firms

	(1)	(2)	(3)	(4)
	_t	_t	_t	_t
_t				
Size	0.000721***	0.000747***	0.000775***	0.000566***
	(0.0000946)	(0.0000952)	(0.0000966)	(0.000162)
Ecosystem	0.000250***	0.000264***	0.000267***	0.0000909
	(0.0000657)	(0.0000658)	(0.0000713)	(0.0000984)
Industry	0.000133***	0.0000366	0.0000195	0.0000612
	(0.0000189)	(0.0000345)	(0.0000940)	(0.0000743)
Entry	0.000160	0.0000922	0.0000802	0.000445
	(0.000202)	(0.000202)	(0.000204)	(0.000229)
Continent	-0.0296	-0.0318	-0.0346	-0.0388
	(0.0266)	(0.0265)	(0.0266)	(0.0336)
Scope	-0.244***	-0.253***	-0.244**	-0.359*
	(0.0338)	(0.0528)	(0.0816)	(0.146)
Bottleneck (Seller/ BoS)		0.174**		
		(0.0657)		
Architect (Equipment / Installer)		0.363***		
		(0.0946)		
Standard (Panel / Material)		0.126	0.0954	0.356
		(0.0812)	(0.0842)	(0.194)
ControlBottleneck (Seller)			0.202**	0.284*
			(0.0718)	(0.131)
CapacityBottleneck (BoS)			0.0693	0.240
			(0.0761)	(0.165)
UpstreamArchitect (Equipment)			0.301**	-0.238
			(0.110)	(0.581)
DownstreamArchitect (Installer)			0.360	
			(0.217)	
Hybrid				0.304***
				(0.0591)
_cons	6.300***	6.150***	6.177***	7.231***
	(0.355)	(0.357)	(0.384)	(0.514)
/				
lngamma	-0.428***	-0.432***	-0.435***	-0.452***
	(0.0334)	(0.0330)	(0.0333)	(0.0438)
lntheta	-1.803	-1.889	-1.806	-0.937
	(0.982)	(1.042)	(0.980)	(0.661)
N	89351	89351	89351	56897

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

TABLE 4. Cox regression results (hazard ratios) based on different ecosystem roles of solar PV firms

	(1) _t	(2) _t	(3) _t	(4) _t
Size	0.999***	0.999***	0.999***	0.999***
	(-7.54)	(-7.68)	(-7.70)	(-3.54)
Ecosystem	1.000	1.000	1.000	1.000
	(0.37)	(0.11)	(0.36)	(-0.40)
Industry	1.000***	1.000	1.000	1.000
	(-7.61)	(-0.92)	(-0.84)	(-1.64)
Entry	1.000	1.000	1.000	0.999
	(-0.88)	(-0.66)	(-0.70)	(-1.70)
Continent	1.004	1.007	1.009	1.056
	(0.14)	(0.22)	(0.29)	(1.46)
Scope	1.311***	1.326***	1.403***	1.497**
	(7.18)	(4.81)	(3.68)	(2.71)
Bottleneck (Seller/ BoS)		0.816** (-2.66)		
Architect (Equipment / Installer)		0.628*** (-4.15)		
Standard (Panel / Material)		0.867 (-1.57)	0.884 (-1.28)	0.708 (-1.67)
ControlBottleneck (Seller)			0.804**	0.748*
			(-2.61)	(-2.11)
CapacityBottleneck (BoS)			0.867	0.837
			(-1.64)	(-1.02)
UpstreamArchitect (Equipment)			0.621*** (-3.82)	1.172 (0.26)
DownstreamArchitect (Installer)			0.753 (-0.91)	
Hybrid				0.667***
				(-5.98)
N	89351	89351	89351	56897

Exponentiated coefficients; *t* statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

TABLE 5. Accelerated failure time estimates (using Inverse-Gaussian shared frailty) based on different dynamic ecosystem roles of solar PV firms

	(5)	(6)
	_t	_t
_t		
Size	0.000687***	0.000712***
	(0.0000940)	(0.0000939)
Ecosystem	0.000235***	0.000226***
	(0.0000649)	(0.0000641)
Industry	0.000142***	0.000144***
	(0.0000189)	(0.0000189)
Entry	0.000142	0.000187
	(0.000198)	(0.000202)
Continent	-0.0305	-0.0210
	(0.0265)	(0.0264)
Scope	-0.302***	-0.291***
	(0.0352)	(0.0352)
Diversify	0.778***	
	(0.236)	
NoChange	-0.212***	-0.242***
	(0.0529)	(0.0528)
Divest		-0.261***
		(0.0495)
_cons	6.593***	6.685***
	(0.356)	(0.348)
/		
lngamma	-0.446***	-0.436***
	(0.0339)	(0.0319)
lntheta	-1.536	-1.823*
	(0.788)	(0.927)
N	89351	89351

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

TABLE 6. Cox regression results (hazard ratios) based on different dynamic ecosystem roles of solar PV firms

	(5)	(6)
	_t	_t
main		
Size	0.999***	0.999***
	(-7.34)	(-7.47)
Ecosystem	1.000	1.000
	(-0.94)	(-1.17)
Industry	1.000***	1.000***
	(-8.37)	(-8.32)
Entry	1.000	1.000
	(-0.16)	(-0.41)
Continent	1.014	1.006
	(0.49)	(0.19)
Scope	1.383***	1.346***
	(8.35)	(7.69)
Diversify	0.0915**	
	(-2.64)	
NoChange	1.755***	1.802***
	(4.83)	(5.06)
Divest		1.330***
		(5.39)
tvc		
Diversify	1.001*	
	(2.04)	
NoChange	1.000***	1.000***
	(-3.90)	(-3.87)
N	89351	89351

Exponentiated coefficients; *t* statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

FIGURES

FIGURE 1. Evolution of the total number of firms in the solar PV industry

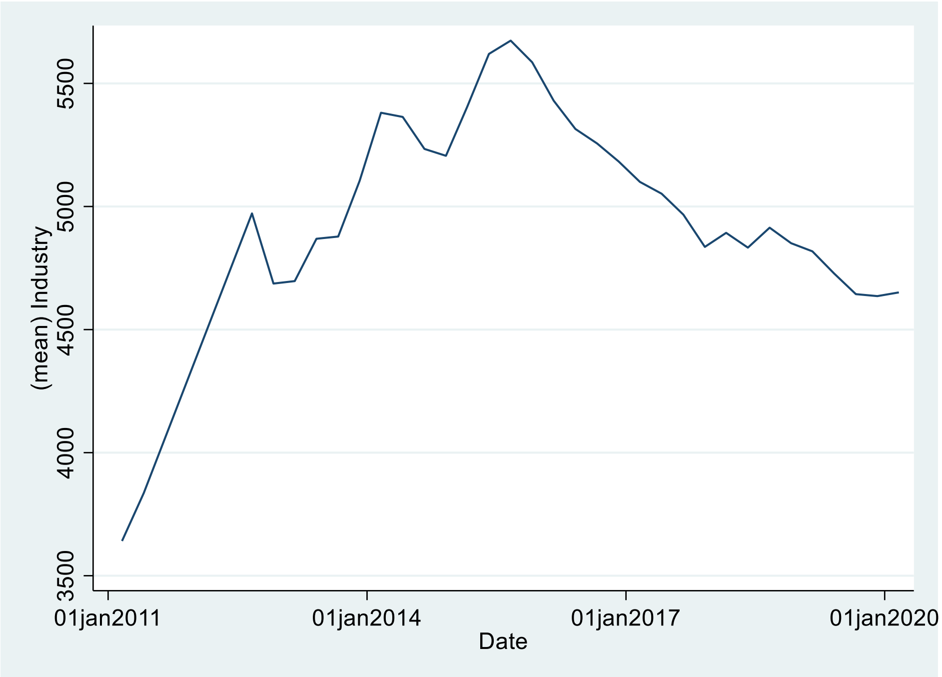
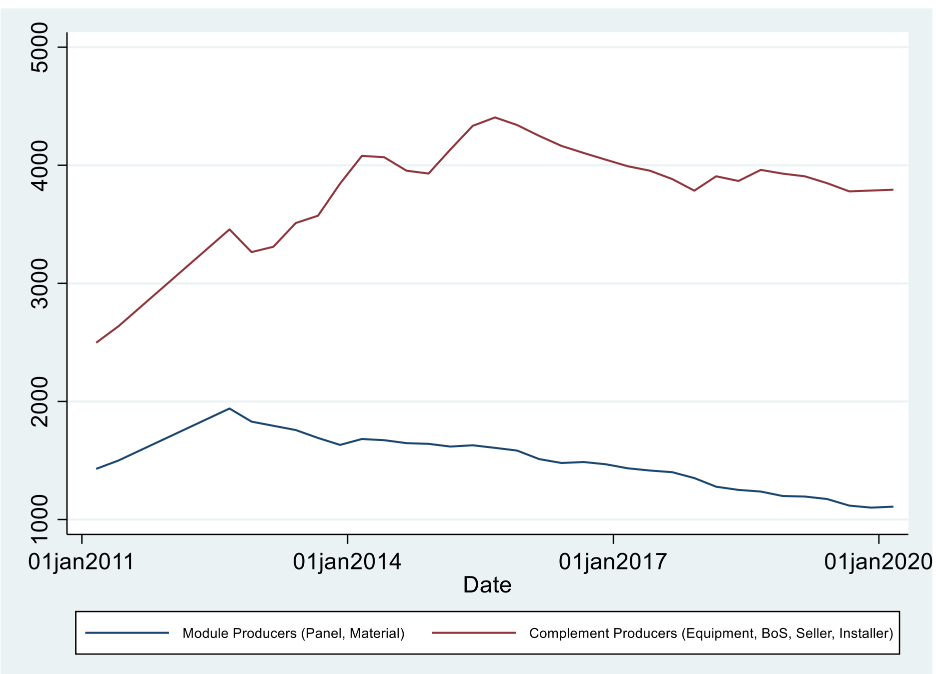


FIGURE 2. Evolution of the number of firms by different ecosystem element produced in the solar PV industry



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