Complementarities and Capabilities: Unpacking the Drivers of Entrants' Technology Choices in the Solar Photovoltaic Industry

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ABSTRACT

Management scholars have studied the process of entry in a new industry from two different perspectives. The first perspective, grounded in technology management, has portrayed entrants as pursuing distinct technological choices during the growth stage of an industry followed by the emergence of a dominant design and industry shakeout. The second perspective, grounded in evolutionary economics and strategy, while being silent on entrants' technology choices has portrayed entrants as either diversifying firms with pre-entry capabilities or de novo startups lacking such capabilities. In this study, we unpack the drivers of entrants' technology choices by considering the role of firm-level pre-entry capabilities and ecosystem-level complementary assets. We test our arguments during the growth stage of the global solar photovoltaic (PV) industry from 1978 to 2011. Although the role of ecosystem-level complementary assets has often been overlooked, we find that an entrant is more likely to choose a technology for which the complementary assets are available in the ecosystem than technologies for which they still need to be developed. As compared to de novo entrants, diversifying entrants are more likely to choose a technology for which complementary assets are available in the ecosystem. This difference between diversifying and de novo entrants is mostly due to diversifying entrants with capabilities that are specialized to the solar photovoltaic industry. The study argues that to understand the process of entry in a new industry, we need to explicitly consider the broader interaction between firm-level pre-entry capabilities and ecosystem-level complementarities.

INTRODUCTION

A well-established literature on industry evolution has characterized an industry in terms of a life cycle model that entails an initial period of entry and market growth, followed by a shakeout in which many firms exit the industry, and then a period of relative maturity and finally decline (e.g., Agarwal and Gort, 1996; Geroski, 1995; Gort and Klepper, 1982; Klepper and Grady, 1990; Utterback, 1996). Scholars in management have paid particular attention to industry emergence and the process of entry as it guides the industry life cycle and shapes firms' performance outcomes. Research grounded in technology management has considered entrants as pursuing distinct technological choices during the initial "fluid" stage characterized by high supply- and demand-side uncertainty (e.g., Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Clark, 1985; McGahan, Argyres, and Baum, 2004; Utterback, 1996; Van de Ven and Garud, 1993). This uncertainty is eventually resolved with the emergence of a dominant design leading to a drastic reduction in technological diversity and industry shakeout. In parallel, research grounded in evolutionary economics and strategy has studied the process of entry by differentiating between diversifying firms and de novo entrepreneurial start-ups (e.g., Carroll *et al.,* 1996; Ganco and Agarwal, 2009; Helfat and Lieberman, 2002; Klepper and Simons, 2000). These pre-entry differences among firms at the time of entry have been shown to have important strategic implications.

While valuable, each of these research streams have on their own offered an incomplete view of entry. On the one hand, scholars in technology management are explicit about the diversity in entrants' technological choices but are silent regarding what drives these differences. On the other hand, scholars in evolutionary economics and strategy are explicit about the differences in entrants' pre-entry capabilities but are silent regarding diversity in their technological choices. Given the importance of firms' technological choices and pre-entry capabilities to the pattern of industry evolution and their performance outcomes (Helfat and Lieberman, 2002; Klepper, 1996; Utterback, 1996), this is an important gap in the literature that this study seeks to bridge.

A central premise in this study is that in an emerging industry, complementary assets are key drivers of a technology's commercialization (Teece, 1986, 2000). These complementary assets may represent firm-level resource or capability endowments (Helfat, 1997; Mitchell, 1989; Tripsas, 1997). They may also represent ecosystem-level complementary activities and technologies that are required for the value creation by the focal technology (Adner and Kapoor, 2010; Teece, 2006). While scholars have considered the role of firms' pre-entry capabilities to study entry decisions, the effect of ecosystem-level complementary assets and their interaction with firms' pre-entry capabilities has received little attention. In this paper, we consider how an entrant's technological choice during the growth stage of the industry is shaped by both firm-level and ecosystem-level complementarities. Specifically we propose that technologies may differ in the extent to which ecosystem-level complementary assets are available.[1] We explore how both the availability of these assets as well as a firm's pre-entry capabilities shape technology choice upon entry. Furthermore, we explore how entrants with specialized versus general pre-entry capabilities may make different pre-entry choices (Helfat and Lieberman, 2002). We argue that these factors represent important differences in the entrants' "utilities" from a given technology and form the basis for their technology entry choices.

We test our arguments in the context of the global solar photovoltaic (PV) industry's emergence from the late 1970s to 2011. The industry has been gaining increasing importance over the last two decades with the emphasis on the renewal energy sector. In addition to its

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[1] Teece (2006) refers to these as bottleneck or choke points in the value chain.

economic and policy prominence, the industry provides an ideal setting in which to examine the drivers of entrants' technology choices in an emerging industry. During the study period, we observe 176 firms (both diversifying and de novo) entering the industry with the number of entrants peaking in 2008 followed by a sharp decline as increasing minimum efficient scale, falling prices, decreasing policy support, and extended global recession dimmed the enthusiasm of new entrants. An important feature of the industry for the purpose of the study is that entrants have pursued four distinct technological choices that vary in the extent to which complementary assets are available in the ecosystem and until today, no clear consensus has emerged regarding which technology would become the dominant design (Ardani and Margolis, 2011; Chopra, Paulson, and Dutta, 2004; Peters *et al.*, 2011).

Although ecosystem-level complementary assets are rarely examined in the literature, we find that they have a profound effect on firms' entry choice: on average, an entrant is more likely to choose a technology for which the complementary assets are available in the ecosystem than technologies for which they have to be developed. In comparing firm-level differences, we find that, as compared to *de novo* entrants, diversifying entrants are even more likely to choose a technology for which complementary assets are available in the ecosystem. This difference between the technological choices of diversifying and de novo entrants is mostly due to diversifying entrants with capabilities that are specialized to the solar photovoltaic industry.

By showing that the observed variation in the technological choices among entrants in an emerging industry can be explained by firm-level pre-entry capabilities and ecosystem-level complementarities, the study sheds light on the previously unexplored but important linkages that exist between the technology management, and the evolutionary economics and strategy perspectives of industry evolution. The findings from the study also argue for a broader assessment of complementary assets to study firms' entry decisions that not only include firm-level pre-entry capabilities (Helfat and Raubitschek, 2000; Klepper and Simons, 2000; Mitchell, 1989) but also ecosystem-level complementary activities and technologies (Adner and Kapoor, 2010; Teece, 2006). Finally, the study reinforces the value of categorizing firms' pre-entry capabilities that are specialized with respect to a given context or generalized across contexts (Helfat and Lieberman, 2002), and shows how this difference has an important effect on firms' entry choices.

THEORY AND HYPOTHESES

The evolution of an industry from its initial growth to maturity has been extensively studied by scholars in management. Great progress has been made in explaining the evolutionary changes (e.g., number of firms, rate of entry and exit, innovative activity) that take place over the life cycle of an industry and the performance differences across firms (cf. Agarwal and Tripsas, 2011 for a recent review of the literature). In this study, we focus on the initial growth stage of the industry that is characterized by a high rate of entry by firms seeking to capitalize on new technological and market opportunities (Geroski, 1995). Scholars have studied the process of entry in a new industry from two distinct perspectives. Those grounded in technology management have viewed entry through the lens of diverse technological choices pursued by entrants which is then followed by the emergence of a dominant design and industry shakeout (Abernathy and Utterback, 1978; Utterback, 1996). Evidence of this phenomenon has been documented in a variety of industries including typewriters, automobiles, electronic calculators, integrated circuits, televisions, disk drives (Suarez and Utterback, 1995; Utterback, 1996), cochlear implants (Van de Ven and Garud, 1993) and fax machines (Baum, Korn, and

Kotha, 1995). While this literature stream acknowledges the technological diversity during the growth stage of the industry, no attempt has been made to uncover the drivers of these initial technological choices which hold important implications for technology competition and industry evolution. By contrast, scholars grounded in evolutionary economics and strategy have viewed entry through the lens of firms' pre-entry resources and capabilities and have shown that pre-entry capability differences between diversifying entrants and *de novo* entrants have an important bearing on their performance outcomes (Carroll *et al.*, 1996; Ganco and Agarwal, 2009; Helfat and Lieberman, 2002; Klepper, 2002; Klepper and Simons, 2000). However, while this literature stream has generated valuable insights regarding the relationship between firms' pre-entry capabilities and performance outcomes, it has tended to ignore the differences in the strategies pursued by entrants in order to compete in an emerging industry. A notable exception is Qian et al. (2012) who explore the sources of differences in entrants' vertical integration choices in the U.S. Bioethanol Industry.

In this paper, we develop a framework that helps to predict entrants' technological choices in an emerging industry. The framework considers such choices in the context of the complementary assets that underlie a given technology's commercialization (Teece, 1986, 2006). Empirical examinations of the role of complementary assets on the firms' entry decisions have focused on firm-level, pre-entry resources or capabilities (Helfat and Raubitschek, 2000; Klepper and Simons, 2000; Mitchell, 1989). For example, Mitchell (1989) found that firms in the diagnostic imaging industry were more likely to enter new technological subfields if they possessed their own distribution system. Similarly, Klepper and Simons (2000) found that radio producers' likelihood of entering the emerging TV industry increased with the extent of their R&D and marketing experience in the home entertainment market. Given the importance of resources and capabilities to entry, Helfat and Lieberman (2002) categorized entrants' pre-entry resources and capabilities, differentiating between resources and capabilities that are specialized to a particular setting (e.g., manufacturing, marketing, distribution) and those that are generalized across a range of settings (e.g., financial capital, knowledge management).

At the same time, while the bulk of attention in the literature on market entry has been devoted to firm-level pre-entry resources or capabilities, complementary assets also reside in the external business ecosystem that encompasses interdependent activities and technologies (Adner and Kapoor, 2010; Teece, 2006). Such complementary assets may play a critical, but unexamined role in firms' entry decisions and strategies (Henderson and Mitchell, 1997; Jacobides and Winter, 2005). As Teece (2006) notes in his reflection on his seminal article, the treatment of complementarities in the original article was somewhat limited. The article, while acknowledging the systemic nature of a technology, focused much more on firm-level value chain (p. 1139). In so doing, it tended to downplay the importance of technological complementarities in the ecosystem which can be a bottleneck asset to value creation by the focal technology. For example, successful commercialization of electric cars depends on the development of batteries with high charging density and low cost as well as the development of the charging infrastructure. Similarly, commercialization of new generations of semiconductor chips depends not just on chip design but also on the development of manufacturing equipment for mass manufacturing of miniaturized circuits (Kapoor and Adner, 2012). Such complementarities have been documented by historians in the context of aircraft engines (Constant, 1980), machine tools (Rosenberg, 1982) and electricity networks (Hughes, 1983), and have only recently been examined in the strategy literature (Adner and Kapoor, 2010). In this study, we explicitly consider both the previously under-examined influence of ecosystem-level complementary assets and firm-level pre-entry capabilities on entrants' technology choices.

The interaction between ecosystem-level complementary assets and firm-level capabilities plays an important role in the evolution of industries (Jacobides and Winter, 2005; Klepper, 1996), particularly during the industry emergence phase when different technologies compete for dominance (Anderson and Tushman, 1990). During this emergence phase, entrants pursuing competing technologies, struggle, under conditions of uncertainty, to establish performance superiority and market dominance (Utterback, 1996). The competition between entrants pursuing distinct technologies does not occur in a sterile vacuum, but instead occurs within the context of the broader ecosystem. Complementary assets within the ecosystem can create catalysts or barriers for specific technologies, reshaping entrant strategy by changing the barriers and costs to choosing and commercializing one technology over another. In turn, the choice regarding which technology to commercialize not only impact firm outcomes, but also the outcome of technology contests more broadly and thus the future of new industries.

As an example, the early automobile industry was characterized by significant technological diversity with entrants pursuing steam, electric, and internal combustion engine technologies in the competition for industry dominance. However, this competition was profoundly shaped by the availability of ecosystem-level complementary assets. Indeed, because steam engine components and production equipment had been developed broadly in locomotives and ships, a rush of early entrants into automobiles pursued steam-driven vehicles—a design that achieved early market share majority. Similarly, a number of entrants pursued internal-combustion engines, seizing on the growing availability of complementary assets as the broader market for combustion engines evolved. By contrast, even though several entrants attempted electric vehicles which were cleaner, quieter, and more popular than internal-combustion designs (including an early Ferrari design), the serious limitations in external complementary assets (lightweight batteries, large electric motors, etc.) dramatically limited entry into and ultimately the survival of electric vehicles. Beyond entry choice, complementary assets in the ecosystem also influenced the later triumph of internal-combustion engines: the development of road networks (most drivable roads were limited to urban areas) expanded the potential range for these vehicles and the development of cheap oil in Texas (which lowered the fuel costs of internal-combustion below those for steam and electric) further shifted competition in favor of internal-combustion engines. Although we often view the evolution of the automobile industry in terms of the superiority of the internal combustion engine, in fact, the competition itself was deeply shaped by the complementary assets in the ecosystem.

To understand the source and role of ecosystem-level complementary assets during the emergence of an industry, it is important to begin with the recognition that the potential for and availability of ecosystem-level complementary assets varies between technologies. Levinthal (1998) and Adner and Levinthal (2002) discuss how the emergence of new technologies often represent speciation events that entail adaptation and recombination of technological know-how from existing application domains towards new application domains. As a result, the availability of complementary assets in the ecosystem can differ significantly between technologies competing for dominance (Adner and Kapoor, 2010). For example, in the solar PV industry, manufacturing equipment represents a critical complementary asset for technology commercialization requiring significant investments of financial and intellectual capital (millions of dollars and years of development). Manufacturing equipment for different PV technologies has emerged at different time periods largely because of the differences in the knowledge and manufacturing processes that could be borrowed from related application domains: crystalline silicon PV manufacturing equipment emerged first, benefiting from the billions of dollars spent in the parallel semiconductor industry, followed by amorphous silicon manufacturing equipment, which also benefitted from earlier developments in the flat panel display industries. By contrast, even though other technologies show potentially greater cost-performance benefits, there are no easily identifiable application domains that could serve as a pre-existing source for manufacturing equipment.

Early entrants can also be a source for the development of complementary assets. Entrants that establish industry-specific complementary assets, such as distribution networks or manufacturing equipment, pay pioneering costs that shape the future technology choices of competitors, depending on the degree to which an early entrant can monopolize the returns to the complementary assets (Teece, 1986). For example, when Edison commercialized the light bulb, he also developed a robust electricity system, including high-voltage transmission so that he could use thinner copper wires to span greater distances required for lower-cost, centralized power generation (Hargadon and Douglas, 2001). Even though Edison could appropriate the value of the light-bulb, the system he developed created opportunities and constraints for future entrants: future entrants could either pay the costs to pioneer and then compete using their own distribution system or they could leverage Edison's system—which most entrants decided to do (Utterback, 1996).

Complementary assets within the ecosystem, therefore, play an important role in entrants' strategic choices and in technology competition. Whether an entrant must invest significant capital or time into creating complementary assets or simply access them in the ecosystem is an important technological choice at the time of entry. If ecosystem-level complementary assets are available for a given technology, they may significantly encourage entry into a technology by lowering the cost and barriers to entering a technology. By contrast, developing complementary assets specific to a new industry can be costly and uncertain, often turning an early entrant advantage into a significant disadvantage (Lieberman and Montgomery, 1998). Similarly the interdependence between assets in a complex system can increase the incidence of mistakes and setbacks while developing industry-specific complementary assets, particularly when an entrant attempts to do so quickly in order to capture a new market opportunity—an effort more likely to result in time-compression diseconomies. Therefore, in an emerging industry with competing technologies, entrants are more likely to pursue a technological path that offers the least resistance to commercialization (i.e., the technology for which complementary assets are available in the ecosystem). Such a path allows entrants to reduce their commercialization risk and leverage the opportunities in the growing industry. Hence, we suggest:

> *Hypothesis 1: During the growth stage of an industry with multiple competing technologies, entrants are more likely to choose a technology for which the key complementary assets within the ecosystem are available than technologies for which the key complementary assets need to be developed.*

Beyond ecosystem-level complementary assets, the difference between entrants' pre-entry capabilities also plays an important role in their technology choices. Entrants are more likely to choose a technology for which the required capabilities match their pre-entry capabilities and experience (Helfat and Lieberman, 2002; Mitchell, 1989). While the literature has often accorded diversifying entrants with pre-entry capabilities, *de novo* start-ups also have a pre-history that may be relevant to their technology choice. For example, founders of these firms likely have the relevant technical and market knowledge required to compete in the new industry (Furr, Cavarretta, and Garg, 2012; Klepper, 2001). However, *de novo* entrants lack the organizational-level capabilities and routines and these would still have to be developed upon entry (Qian *et al.*, 2012). Hence, an important difference between diversifying and *de novo* entrants is that while entry by *de novo* entrants coincides with capability development and the initiation of their capability life cycle, entry by diversifying entrants coincides with capability redeployment and continued development of the capability within a new application domain (Helfat and Eisenhardt, 2005; Helfat and Peteraf, 2003).

This difference between diversifying and *de novo* entrants alters their relative incentives with respect to technology choices. Diversifying entrants with a higher stock of pre-entry capabilities than de novo entrants are likely to benefit more from redeploying their capabilities into technologies for which the complementary assets are available in the ecosystem than for technologies for which the complementary assets will have to be developed for commercialization to take place. This is because diversifying entrants stand to gain more from the firm-level and ecosystem-level complementarities with technologies that not only match their pre-entry capabilities but also do not face a significant bottleneck to value creation. For example, a diversifying entrant with experience and capabilities in high-throughput electronics manufacturing can more readily leverage the availability of PV manufacturing equipment to enter and commercialize a PV technology than a de novo entrant lacking these organizational capabilities.

By contrast, de novo entrants often have an incentive to pursue technologies for which complementary assets need development because it provides an opportunity to maximize the development of new capabilities (Methé, Swaminathan, and Mitchell, 1996). This is because *de novo* entrants can pursue the development of both stage-specific and integrative capabilities that enable communication and coordination across interdependent stages in the ecosystem (Helfat and Winter, 2011; Qian *et al.*, 2012). In so doing, they are able to differentiate from diversifying entrants and build capabilities that offer a path to sustainable competitive advantage (Fortune and Mitchell, 2012; Helfat and Raubitschek, 2000). Accordingly, we suggest:

> *Hypothesis 2: The likelihood of choosing a technology for which the complementary assets are available in the ecosystem will be greater for diversifying entrants than for de novo entrants*.

At the same time that diversifying entrants have a greater stock of pre-entry organizational capabilities than *de novo* entrants, diversifying entrants differ in the degree to which their pre-entry capabilities match the capabilities required for that industry (Klepper, 1996). Helfat and Lieberman (2002) distinguished between the pre-entry capabilities that are specialized to a given context (e.g., technological knowledge) and those that are generalized across contexts (e.g., corporate-level capability of managing and/or generating synergies across businesses). The categorization builds on Chatterjee and Wernerfelt (1991), who consider how the flexibility of firms' resources shape the extent to which firms pursue related or unrelated diversification. These arguments propose that the more specialized the diversifying entrant's pre-entry capability towards the new emerging industry, the greater the benefits that firms derive from entering the related industry (Bettis, 1981; Rumelt, 1974).

If ecosystem level complementary assets are available, entrants possessing specialized pre-entry capabilities are likely to obtain greater benefit from firm-level and ecosystem-level complementarities than those entrants with generalized pre-entry capabilities. Even when ecosystem-level complementary assets are available, firms must still develop the capabilities to deploy those complementary assets. When the relatedness gap between the capabilities to deploy complementary assets is low, the cost of developing new capabilities may also be low and thus entrants can more quickly maximize the benefit of any particular complementary asset (Bryce and Winter, 2009; Nelson and Winter, 1982; Winter, 2003). Specifically, possessing specialized rather than generalized pre-entry capabilities lowers the cost of developing the full portfolio of capabilities necessary for production, as well as the cost of developing the integrative capabilities to maximize the value of complementary assets available in the ecosystem (Helfat and Peteraf, 2003; Helfat and Raubitschek, 2000). Therefore, as compared to diversifying entrants with generalized capabilities, diversifying entrants with specialized capabilities would gain more from the firm-level and ecosystem-level complementarities. Accordingly, we propose:

> *Hypothesis 3: The likelihood of choosing a technology for which the complementary assets are available in the ecosystem will be greater for diversifying entrants with pre-entry capabilities that are specialized to the industry than for diversifying entrants with pre-entry capabilities that are generalized across industries*

EMPIRICAL CONTEXT

We explore our arguments in the context of the global solar photovoltaic (PV) module manufacturing industry during its period of emergence from 1978 to 2011. The solar PV industry has been one of the most important pillars of the renewal energy sector which also includes wind, geothermal and hydro energy. In addition to its economic and policy prominence, the industry provides an ideal setting in which to examine the drivers of entrants' technology choices in an emerging industry. During the period of study, entrants, both diversifying and *de novo*, pursued four distinct technological paths with no consensus in the industry as to which technology was a superior option (Chopra *et al.*, 2004; Peters *et al.*, 2011). The four technologies not only represented a complex set of tradeoffs but also differed in the extent to which the ecosystem-level complementary assets were available to facilitate commercialization.

Another important feature of the industry, for the purpose of the study, was that the number of entrants gradually increased during the 1980s and 1990s, peaked in 2008, and then declined sharply in the following years, accompanied by rising exits. Hence, despite the industry's somewhat recent emergence, our analysis captures almost the entire wave of entry into an emerging industry.

Data

We used both primary and secondary data sources for the study. We conducted extensive fieldwork spanning 36 months between 2006 and 2012 to understand the evolution of the solar PV module industry, the different types of technologies pursued by entrants, the nature of complementary assets and the factors influencing entrants' technology choices. We interviewed over thirty industry professionals that included employees of solar PV firms, industry analysts/consultants, and solar PV scientists as well as conducted several visits to solar PV manufacturing plants, research labs, and industry conferences. These interviews and visits entailed semi-structured interviews based on an interview guide, lasting from an average 1.5 hours interview to full-day site visits, as well as open-ended discussions. In addition, one author sat on the board of a solar industry association to better understand the challenges and strategic considerations for industry participants. Finally, we conducted a thorough review of the two most comprehensive industry trade journals: *PV News*, the single longitudinal record of the PV industry with the mission to independently chronicle the emergence of the solar industry, as well as *Photon International*, the longest running trade journal dedicated to tracking the broader solar PV ecosystem.

For the quantitative analysis, we drew on the proprietary industry database maintained by Greentech Media (www.greentechmedia.com). Greentech Media is widely regarded as the leading industry consultant organization for the solar PV industry. The database included information on a total of 176 publicly-listed and privately-held solar PV firms that competed in the industry since the industry's beginnings. We also checked the identity of the firms listed in the Greentech Media database against an annual survey conducted every year since 1999 by Photon International, of all solar modules ever produced. We gathered self-reported data on firms' entry year, their technology choices and pre-entry characteristics from company websites, public filings and through personal communication. We then corroborated these data against multiple industry reports produced by Greentech Media, Photon International, and other industry analysts, and found them to be highly consistent across the different sources. Finally, data on industry sales and technology performance was obtained from *Progress in Photovoltaics* Journal, *Photon International* and the U.S. Department of Energy's National Renewable Energies Lab (www.nrel.org) (Green *et al.*, 2012).

Industry Background

Solar photovoltaic (PV) modules are devices that convert sunlight into electrical energy through the photovoltaic effect first observed by Alexandre-Edmond Becquerel in 1839. A typical solar PV module includes between 36 and 72 solar cells (the photovoltaic component of a solar PV module that converts light into energy) that are connected to each other to generate current. Early research explored the applicability of different types of materials as potential candidates for the solar cell. An ideal material candidate has an atomic structure that allows energy from sunlight to displace electrons and generate electric current. The materials currently in commercial use include crystalline silicon, amorphous silicon, cadmium telluride, and CIGS (Copper Indium Gallium Di-Selenide). The first terrestrial solar PV module was not developed until 1955 by Bell Labs and was soon followed by several mostly failed attempts to produce PV modules on a small scale for niche market applications such as aerospace and lighthouses (notable efforts were made by National Fabricated Products, Sharp, and RTC). The oil crisis of the 1970s provided the first real ignition point for a commercial solar PV market, leading to the entry of several firms attempting to commercialize solar PV modules (Bradford, 2006; Green, 2005; Lynn, 2010).

The resolution of the oil crisis in the 1980s and slackening institutional support led to a market collapse and slow global growth until the 1990s when the re-emergence of global energy and environmental concern led to policies that reinvigorated the solar industry (Japanese Sunshine program, German 100,000 solar roofs, U.S. energy policy, Kyoto Protocol under the earlier United Nations Framework on Climate Change among others). As a result of these policies, the industry saw a significant increase in the number of entrants leading to a thirty-three fold increase in annual global production from 2000 until 2010 that tripled again during the following two years (Henderson, Conkling, and Roberts, 2007; Hering, 2012; Nemet, 2006). Figure 1 depicts the pattern of entry into the solar photovoltaic industry. The number of entrants peaked in 2008 and declined rapidly thereafter as a result of intense competition, excess capacity, global financial crisis and weakening policy support. The observed entry pattern in the Solar PV industry is consistent with the industry evolution literature with the takeoff in the number of firms preceding the takeoff in industry sales (Agarwal and Bayus, 2002).

(Insert Figure 1 about here)

Entrants' Technology Choices

The emergence stage of the solar PV module industry was characterized by entrants pursuing four distinct technology choices (see Figure 2). Underlying these technology choices was the choice of the material that is used to convert energy from sunlight into electricity. Each technology represented not only distinct technical know-how but also specialized manufacturing capital investments often exceeding $100M for a single manufacturing plant.

(Insert Figure 2 about here)

A prominent technology choice for entrants was based on crystalline silicon (c-Si) material. C-Si modules are produced by assembling, interconnecting, and laminating c-Si solar cells (themselves produced by first growing a silicon ingot of high-purity in a quartz crucible, slicing the ingot into wafers, and then doping and processing wafers into cells). Because c-Si has a highly ordered atomic structure, these modules are the highest efficiency solar technology (meaning they convert the highest percentage of sunlight into electricity), but they are also higher cost due to the many processing steps and the sheer quantity of semiconductor material used (often c-Si cells are 200-300 microns (10^{-6} m) thick whereas the semiconductor material in the alternative CdTe technology is only 5-6 microns thick). Crystalline silicon cells are produced in two interchangeable variants: mono-crystalline which are single crystal, higher efficiency, and higher cost to manufacture, or poly-crystalline which are composed of multiple crystals and thus slightly lower efficiency and lower cost to manufacture.

By contrast, amorphous-silicon (a-Si) - unstructured silicon with very different atomic properties than c-Si emerging as a commercial alternative in the 1980s - can be quickly sprayed in a thin layer (<1 micron compared to the 200 micron thick silicon wafer in c-Si) onto a substrate and manufactured much more quickly, yielding the lowest production costs but also the lowest efficiency of all modules (Takahashi and Konagai, 1986). In addition to low material usage, lower cost, and simpler manufacturing, a-Si also has better absorption of mid-day sun and a lower temperature coefficient, which means more energy can be produced per installed watt of modules than c-Si (Chopra *et al.*, 2004). These advantages are offset by the fact that a-Si has the lowest actual cell efficiency (less light per unit of area is converted into electricity), which tends to decrease slightly after initial exposure to light (Staebler and Wronski, 1980).

CIGS technology, an abbreviation for the semiconductor materials in this four-layer cell (Copper, Indium, Gallium, Di-Selenide) emerged as a commercial competitor in the mid-1990s. CIGS offered the benefits of potentially high sunlight conversion efficiencies (research cell efficiencies approach those of crystalline silicon), low material use (3-5 microns of semiconductor material), long-term output stability, and most promising—potential for high-throughput, roll-to-roll manufacturing that could reach 1,000 feet per minute (c-Si modules can take several minutes per foot to manufacture) (Chopra *et al.*, 2004; del Cañizo, del Coso, and Sinke, 2009). The most significant challenge faced by CIGS technology has been the complexity of manufacturing a high-performing, four-layer module.

Finally, Cadmium Telluride (CdTe) modules emerged as another technological alternative before industry takeoff. CdTe modules offered the promise of moderate efficiencies (better than a-Si, less than CIGS), optimal absorption of the solar spectrum (well-matched bandgap), and simpler manufacturing than CIGS, but battled perceptions of Cadmium toxicity.

Which of the four technologies was superior remained a question of significant debate within the industry during this entire period (Bradford, 2006; Chopra *et al.*, 2004; Grama and Bradford, 2008; Peters *et al.*, 2011). Table 1summarizes the key performance tradeoffs for each of the technology choices. Proponents of c-Si point to the robustness of the material science behind crystalline silicon, whereas proponents of amorphous silicon argue that their technology has the highest chance of reaching the scale needed to capture majority market share. Similarly producers of CIGS cite that their technology has high efficiency whereas CdTe advocates, which has intermediate level of efficiency, argue that their technology has actually reached greater manufacturing scale and overcome toxicity criticisms through recycling programs. In summary, the debate about which technology would actually be superior continued throughout industry emergence. Furthermore, every technology was chosen by and developed by both major diversifying firms (BP, GE, Sharp, etc.) as well as a keenly followed *de novo* start-ups (First Solar, Solar Frontier, Trony Solar, etc.). Finally, the reported spot market prices among the different technologies have remained nearly identical. Although many have picked their favorite “horse,” the majority of industry analysts and government agencies conclude that it is still too difficult to identify the “winning” technology (Ardani and Margolis, 2011; Grama and Bradford, 2008; Mehta, 2010). Indeed, in a recent peer-reviewed study published in the premier energy journal, Peters et al. (2011) conclude that “it is unclear which solar technology is and will prove most viable.”

(Insert Table 1 about here)

Complementary Assets in the Ecosystem

The core technological know-how for solar PV module needs to be combined with complementary assets and capabilities for entrants to create value through commercialization. While diversifying entrants were endowed with complementary capabilities such as those in manufacturing and marketing, all entrants required solar PV manufacturing equipment—expensive and complex manufacturing equipment with significant embedded technology specific knowledge—to mass produce solar PV modules. In the production of PV modules there are several types of specialized manufacturing equipment (specialized to a specific technology) that play a particularly important role in a firm's ability to commercialize PV modules. The most important among these are the 1) deposition equipment that creates the semiconducting portion of the solar cell and 2) the contact equipment that creates the conductive grid that exports current from the semiconductor material to the electric contacts (Papathanasiou, 2009; Richard, 2010).[2] These equipment are technologically complex and their development represent vast investments of intellectual and financial capital. If such equipment are readily available on a commercial basis, entrants' commercialization challenge entails debugging the equipment during an extensive "pilot" production process so as to achieve high productivity for mass production. In the absence of such equipment, entrants' commercialization challenge also entails selecting and modifying equipment from parallel industries. Modifying manufacturing equipment represents the single, largest challenge many entrants face other than achieving a high productivity manufacturing process.

The availability of these key complementary assets for the solar PV entrant has differed dramatically between technologies. Crystalline silicon benefited from the spillovers from the

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[2] Note that while there are many different types of downstream complementary assets within the solar PV industry such as distribution channels and inverters, these complementary assets are not specialized to a given technology. Therefore, we focus on the upstream complementary assets, the most important of which are the deposition and contact manufacturing equipment required for producing solar PV modules.

semiconductor and electronics equipment industries, leading to the early commercial availability of manufacturing equipment with the deposition equipment first available in 1984 and the contact equipment first available in 1994. Similarly, the manufacturing equipment for amorphous silicon benefited from developments in thin film technologies, displays and other industries leading to the availability of specialized deposition equipment for the critical layer of semiconductor material in 1989 and contact equipment in 2005. By contrast, although CIGS and CdTe provided an arguably more attractive technical opportunity than a-Si (these technologies had much higher lab and production efficiencies than a-Si), commercial manufacturing equipment was available much later. The primary reason for the lack of production-ready equipment was not a lack of incentives for the equipment suppliers to develop the equipment, but rather the comparative technical challenges of developing the equipment, a problem exacerbated by the fact that some solar PV technologies could draw very little on developments in other industries. In discussing the challenges of developing equipment for CIGS and CdTe PV technologies, industry expert Paul Maycock stated that “the [equipment] was just so much more complicated than for crystal silicon. It [c-Si] could borrow from all the work and all the equipment in semiconductors” (Maycock, 2013). As a result of these challenges, the core deposition equipment for CIGS was not offered for sale commercially until 2007 (and then only a partial solution) and although contact equipment appeared the year later, only a single model was offered by one manufacturer. For CdTe, deposition equipment was not available until 2011 and contact equipment has been promised but little has been delivered. Hence, entrants into technologies lacking the commercial availability of these key complementary assets had to develop their own manufacturing equipment, often by modifying more generic equipment developed for another industry or purpose. Such developments represented intensive capital and technical investments—for example, the equipment produced by FHR/Centrotherm to deposit the conductive layer on top of a CIGS module (just the electrical contacts, not the actual semiconductor layer) is 33 meters in length, weighs 130 tons, and costs nine million U.S. dollars (Papathanasiou, 2009). In speaking about having to develop their own equipment, one industry CEO stated, "It is a challenging technical problem in the sense that we have to do all things from beginning to end" (Burke, 2007). Despite these challenges, given the technical and economic potential, many entrants did invest in developing equipment for these technologies. In rationalizing adopting a technology lacking these complementary assets in the ecosystem, one investor stated "if it worked it could be revolutionary, it could change the fabric of the solar market and we thought it could" (Atluru, 2007).

EMPIRICAL ANALYSIS

Dependent Variable

Our hypotheses predict entrants' technology choice during the growth stage of the solar PV industry. The dependent variable, *entry choice*, is a binary variable equal to one for the solar PV technology that a firm chose to enter the industry with, and zero for the other technological alternatives that were commercially available in the year of entry. Given the large scale of technology-specific investments, all entrants chose to commercialize only one technology. Out of 176 entrants, 12 firms did pursue other technological alternatives in the later years. This was in part driven by the eventual availability of complementary assets and in part driven by the desire of firms to diversify their technology risk given the pervasive uncertainty about which technology might emerge as the dominant design.

Independent Variables

We employ two binary variables to capture the effect of the availability of complementary assets in the ecosystem on the entrant's technology choice. The first binary variable, *deposition*, takes a value of one if the deposition equipment necessary to deposit the semiconducting layer of the solar cell was commercially available in the year prior to entry, and zero otherwise. The second binary variable, contact, takes a value of one if the equipment required for implanting the electrical contacts on the cell was commercially available in the year prior to entry, and zero otherwise. The timeframe for the commercial availability of equipment is identified based on the suppliers' self-reported information in the Photon International annual equipment surveys as well as their product specifications.

Testing of Hypothesis 2 required that we categorize firms into *diversifying* and *de novo* entrants. An entrant was categorized as a diversifying entrant if it was an established firm operating in another industry before its entry into the solar PV industry (Agarwal *et al.*, 2004; Helfat and Lieberman, 2002), and de novo otherwise. We note that while categorizing entrants into diversifying and de novo entrants represent a dominant categorization schema in the literature, scholars have also identified two other type of entrants – spinouts and incumbent-backed ventures, in the context of the industry's evolution (Agarwal *et al.*, 2004). Spinouts are entrepreneurial ventures of ex-employees of industry incumbents and incumbent-backed ventures are separate legal entities with formal ties (i.e., joint venture, subsidiaries) to the incumbents. Hence, spinout is a sub-category of de novo entrants and incumbent-backed ventures represent a hybrid between de novo and diversifying entrants. Because we are focusing on the early emergence stage of the industry, spinouts and incumbent-backed firms represented a small proportion of our sample (12%). For our main analysis, we classified these firms as de novo entrants. As a robustness check, we exclude them from the analysis and found the results to be qualitatively similar.

Finally, Hypothesis 3 argued that diversifying entrants with specialized rather than generalized pre-entry capabilities would be more likely to enter technologies for which ecosystem-level complementary assets are available. To classify pre-entry capabilities, we identified a diversifying firm's self-reported primary industry classification according to the North American Industry Classification System (NAICS). Based on the description for each of the NAICS code, and following Teece (1986) and Helfat and Lieberman (2002), we categorized each diversifying entrant as having specialized or generalized pre-entry capabilities. Specialized capabilities are those capabilities that are directly applicable in the solar PV industry. These include semiconductor manufacturing capabilities, marketing and distribution capabilities related to customer relationships and understanding of customer preferences in the solar PV industry. We discussed the concordance between NAICS classification and specialized vs. generalized pre-entry capabilities with solar industry experts who agreed unanimously with our categorization. Although it may appear that diversifiers from some manufacturing industries (e.g., automotive) might have capabilities applicable to manufacturing solar PV, given the specialized technical nature of mass manufacturing of semiconductor devices, solar experts confirmed our assessment that we classify those firms as having generalized pre-entry capabilities. Table 2 summarizes the concordance between NAICS classification and diversifying entrants' pre-entry capabilities, and our corresponding rationale..

(Insert Table 2 about here)

Control Variables

Although industry observers, researchers, and market prices suggest that it is difficult to claim that one technology was superior to another during the period of the study, we nonetheless tried to control for any other inherent technology characteristics that might make one technology more attractive to an entrant in a given year. Because different technologies have different fundamental efficiency bands but also different costs, direct comparison of technologies by efficiency alone is impossible (i.e., c-Si has high efficiency but high cost whereas a-Si has low efficiency but low cost). Price per watt has emerged as a widely used, although imperfect comparison measure for technology (actual costs per watt are usually highly guarded secrets). In preliminary models we employed the average price per watt data derived from all available spot price data. This variable was positive, not significant, and supported the hypothesized results as reported. However, price per watt data can only be obtained for a limited number of years, significantly reducing the sample. Therefore, to compare technologies across the entire sample, we created a measure *technical superiority*, which estimates cost per watt by taking the cost per watt in 2011 for each technology, calculated based on the average cost per watt for the subsample of firms that did reveal their costs (Mehta, 2010), then adjusted these costs retrospectively for changes in input costs and efficiency in earlier years. The hypothesized results proved robust to several alternate measures varying the contribution of input costs or variations in adjusting for efficiency. We also employed the variable, *technical opportunity*, measured by the ratio of highest available production efficiency available after three years and highest available production efficiency available in the current year. This helps to control for the potential for technology improvements that may make one technology more attractive than another to a forward looking entrant. As a robustness check, we tested alternate measures including the ratio and difference between the NREL record research efficiency (highest efficiency achieved in research lab) and the highest available production efficiency in a given year. These measures produced similar estimates without qualitatively changing the results for hypothesized effects.

An entrant's technology choice may also be affected by the number of firms in a given technology at the time of entry. We include a variable *firm count by tech*, a continuous variable measuring the total number of firms that are pursuing the focal technology (cSi, aSi, CdTe or CIGS). To control for the relative market share of these technologies, we include the control variable *annual production*, which is the annual production in megawatts for a given technology in a given year. Besides competitive and market share effects, these variables also help to control for the "chicken-and-egg" problem that equipment suppliers may not develop complementary assets for purchase until sufficient firms have entered the industry with a given technology or if there is sufficient level of production volume with a given technology. Finally, in order to control for the technology-level learning curve effects, we included a control variable *cumulative production*, which is the logarithm of the cumulative production in megawatts for a given technology in the year of entry.

Model

Each entrant chooses one technology among the set of available technology alternatives. Our arguments assume that an entrant chooses the technology that offers her the highest level of utility, and we employ a conditional logit discrete choice model to test our predictions (McFadden, 1974). Conditional logit models have been well established as an appropriate approach for modeling firms' entry choices within the strategy literature (Hoetker, 2006; Kalnins and Chung, 2004; Myles Shaver and Flyer, 2000). If $\mathbf{X}_{ij}$ represent the vector of technology-specific attributes for an entrant i with technology j, the utility (U_{ij}) that an entrant derives from choosing a given technology is

$$U_{ij} = \boldsymbol{\beta}'\mathbf{X}_{ij} + \varepsilon_{ij}$$

Where **β’** is the vector of coefficients to be estimated and ε_{ij} is an unobserved random term reflecting unobserved heterogeneity in entrants’ decision making. The conditional logit model estimates the probability that an entrant i choses technology j among n choices. The probability function is given by:

$$Prob\ (Y_i = j) = \frac{\exp\left(\boldsymbol{\beta}'\boldsymbol{X}_{ij}\right)}{\sum_{j=1}^{n} \exp\left(\boldsymbol{\beta}'\boldsymbol{X}_{ij}\right)}$$

Note from the above equation that those variables that do not vary over the technology alternatives simply cancel out. Hence, the conditional logit model provides estimates that are robust to unobserved entrant characteristics that are constant across the technology choices.

RESULTS

We first provide some descriptive evidence that is consistent with our arguments and we then present our regression results**.** Table 3 provides a breakdown of the total number of entrants choosing a particular technology. The number of entrants is significantly greater for technologies for which the deposition and contact equipment were readily available during the emergence stage (c-Si and a-Si) than for technologies for which they had to be developed by the entrants (CdTe and CIGS). Furthermore, in examining the distribution of *de novo* versus diversifying entrants for the specific technologies, the proportion of diversifying entrants is significantly greater for c-Si (63%) and a-Si (63%) than for CdTe (20%) and CIGS (37%). Finally, when distinguishing among diversifying entrants, diversifiers with specialized pre-entry capabilities are a large majority in c-Si and a-Si technologies. These descriptive patterns, while not sensitive to the timing of complementary assets availability, provide some preliminary evidence that seem consistent with our predictions.

(Insert Table 3 about here)

Table 4 presents the descriptive statistics and correlations for the variables used in the regression analysis. Table 5 reports the results from the conditional logit models. Model 1 is the baseline model with control variables. Model 2 includes the effect of availability of deposition equipment and contact equipment to test Hypothesis 1. Hypotheses 2 and 3 could be tested using two distinct approaches. The first approach entails interacting the type of entrants with the covariates for complementary assets. However, this approach assumes that the unexplained variance is same across the different groups of entrants (Allison, 1999). Violation of this assumption can lead to false inferences regarding the differences between groups (Hoetker, 2007). The second approach relaxes the assumption of equal unexplained variance across entrant groups by estimating the model separately for each type of entrant. However, it does not allow for a direct statistical comparison of coefficients across groups. The statistical inferences can only be drawn if coefficients are significant in one group but not in the other or by comparing the ratio of coefficients for two covariates across groups (see Hoetker, 2006). Given that diversifying and de novo entrants have distinct sets of capabilities and motivations, the assumption of identical unobserved heterogeneity underlying their technology choices is likely to be violated. Hence, we test Hypotheses 2 and 3 by estimating separate models for the different types of entrants. Models 3 and 4 report estimates for diversifying and *de novo* entrants respectively, and allow us to test Hypotheses 2. Models 5 and 6 report estimates for diversifying entrants with specialized and generalized capabilities, and allow us to test Hypothesis 3.

(Insert Table 4 about here)

The results from the baseline model are consistent with our expectations. The higher the performance of a given technology, the greater the likelihood of entry in that technology. The likelihood of entry into a technology also increases with the number of firms in that technology possibly due to inter-firm spillovers and/or perceived legitimization of the technology. The effect of technical opportunity, annual production and cumulative production was insignificant.

In Hypothesis 1, we predicted that the likelihood of entry into a given technology increases with the availability of key complementary assets in the ecosystem. The significant positive coefficient for contact equipment provides support for the hypothesis. Entrants are more likely to choose a technology for which the equipment for creating electrical conducting contacts for mass production is available. The coefficient for deposition equipment is positive but insignificant. The results suggest that while entrants' technology choices are constrained by the availability of contact equipment, they may be willing to enter the industry and develop their own deposition equipment for mass manufacturing.

(Insert Table 5 about here)

In Hypothesis 2, we predicted that the likelihood of choosing a technology for which the complementary assets are available in the ecosystem will be greater for diversifying entrants than for de novo entrants. Models 3 and 4 report the estimates for diversifying and de novo entrants respectively. The coefficient for deposition tool is significant only for diversifying entrants.

Hence, the availability of deposition equipment seems to only influence the technology entry choice for diversifying entrants but not for de novo entrants, providing support for Hypothesis 2. While the coefficient for contact equipment is significant for both diversifying and de novo entrants, a comparison of ratio of coefficients for contact equipment and technology performance across the two entrant groups provides an estimate for the relative importance of contact equipment for diversifying and de novo entrants. The ratio is 1.83 for diversifying entrants and 1.18 for de novo entrants, and the difference is statistically significant ($p < 0.01$). Thus, as compared to de novo entrants, diversifying entrants are willing to give up almost 65% of technology superiority for the availability of contact equipment as they choose the technology with which to enter the industry, providing further support for Hypothesis 2.

In Hypothesis 3, we predicted that among diversifying entrants, the likelihood of choosing a technology for which the complementary assets are available in the ecosystem will be greater for diversifying entrants with pre-entry capabilities that are specialized to the industry than for diversifying entrants with pre-entry capabilities that are generalized across industries. The estimates in Models 5 and 6 support the hypothesis. The coefficient for the key complementary assets required for mass manufacturing of PV modules are only significant for diversifying entrants with pre-entry capabilities that are specialized to the Solar PV industry. Hence, the technology preference of diversifying entrants based on ecosystem-level complementary assets is mostly attributable to firms with specialized pre-entry capabilities. These are the firms that derive the greatest complementarities between their pre-entry capabilities and complementary assets in the ecosystem.

We performed additional robustness checks in order to ensure that our inferences are not affected by our modeling and variable choices. We excluded spin-outs and incumbent backed entrants from the analysis in order to confirm that our estimates are not influenced by the somewhat imperfect categorization of these entrants as de novo and diversifying entrants (e.g. Agarwal *et al.*, 2004). We also estimated a model treating the hybrid incumbent-backed entrants as de alio and spin-outs as de novo. Because entry into all four PV technologies was observed only after 1999, we estimated a model excluding all entrant data before that year. Finally, we explored a number of alternative measures for the commercial availability of deposition and contact manufacturing equipment. Our primary measures for deposition and contact equipment take a value of one even if there is only one equipment supplier offering commercial manufacturing equipment for the given technology. We tightened this constraint by raising the threshold for the required number of suppliers to at least two or three suppliers for each equipment type. We also created a joint measure for the deposition and contact equipment which takes a value of one only if both of these equipment types were commercially available. The results were robust to these alternative analyses.

DISCUSSION

The emergence of new industries is characterized by entrants pursuing distinct technological choices followed by the selection of a dominant design and industry shakeout (Utterback, 1996). Yet the drivers of diversity in technological choices have received limited attention. In this study, we develop a framework that helps to predict entrants' technology choices in an emerging industry. We consider a given technology in the context of the complementary assets that reside within the business ecosystem and that are required for successful commercialization (Adner and Kapoor, 2010; Teece, 1986, 2006). We consider a given entrant as either a de novo entrant or a diversifying entrant with pre-entry capabilities (Ganco and Agarwal, 2009; Helfat and Lieberman, 2002; Klepper and Simons, 2000).

We explore our arguments during the emergence of the global solar PV industry in which entrants pursued four distinct technological choices. We find that an entrant is more likely to choose a technology for which the key complementary assets are commercially available in the ecosystem than the technology for which they would have to be developed. As compared to de novo entrants, diversifying entrants aiming to redeploy their capabilities in new industries are more likely to enter with technology for which complementary assets in the ecosystem are available. This difference between diversifying and de novo entrants is primarily due to diversifying entrants with pre-entry capabilities that are specialized to the solar PV industry rather than those with capabilities that are generalized across industries.

The study integrates the technology management perspective of industry evolution with that of evolutionary economics and strategy to explain the drivers of entrants' diverse technology strategies in an emerging industry. While scholars have generated important insights in linking firms' pre-entry capabilities with their entry decisions (Helfat and Raubitschek, 2000; Klepper and Simons, 2000; Mitchell, 1989), these explorations have been silent regarding the role of complementary assets in the ecosystem that underlie firms' value creation (Teece, 2006). By showing that entrant strategies are not only influenced by the complementary assets in the ecosystem but also that this influence is asymmetric across diversifying and de novo entrants, we shed light on the important interaction between firm-level and ecosystem-level complementarities in an emerging industry.

Scholars in technology management have long considered variation in technological choices pursued by entrants during the emergence of an industry. However, no attempts have been made to systematically characterize these technologies and explain entrant strategies. By characterizing technologies according to the extent of development required for complementary assets in the ecosystem and by considering differences in capabilities among diversifying and de novo entrants, the study shows that this observed variation is not random. Rather it is a result of entrants pursuing boundedly rational choices in an industry environment characterized by high levels of growth and uncertainty. Indeed, de novo entrants appear to consider not just their pre-entry capabilities, but the capabilities of other entrants and the broader ecosystem in choosing a technological niche where they have a greater chance of successfully developing and defending an advantage. Similarly, diversifiers are rational in their choices to identify interactions between their own capabilities and the complementary assets in the ecosystem that can be leveraged to quickly commercialize a technology and obtain a defensible advantage.

The finding that the entrant's likelihood of choosing a technology for which the complementary assets are available in the ecosystem is greater for diversifying entrants with pre-entry capabilities that are specialized to the industry than for diversifying entrants with pre-entry capabilities that are generalized across industries confirms the importance of distinguishing between these types of pre-entry capabilities (Helfat and Lieberman, 2002; Teece, 2006). While the empirical literature has often focused on de novo and diversifying entrants, the study reinforces the need for a finer categorization of entrants' pre-entry history.

The study has a number of limitations which provide opportunities for future research. First, it is carried out in the context of a single industry and there is a need to establish the generalizability of our findings in other contexts. Second, while the solar PV industry presented an opportunity to study an important and emerging industry, the variation in ecosystem-level complementary assets across the different technologies is confined to the manufacturing equipment. Clearly, the spectrum of complementary assets is much broader, and it would be interesting to see whether and how these findings may vary depending on the nature of the complementary assets. For example, it would be worthwhile to analyze if firms' entry choices exhibit the same level of sensitivity with complementary technologies that lie downstream as they do with upstream technologies (e.g., Adner and Kapoor, 2010). Third, our measure of availability of complementary assets in the ecosystem is based on the year in which the key manufacturing equipment of deposition and contact were commercially available. The measure is not sensitive to the "quality" of the equipment and which may be an important driver of entrants' technology choice.

CONCLUSION

We explore the drivers of entrants' technology choices in an emerging industry by considering the role of firm-level pre-entry capabilities and ecosystem-level complementary assets that allow for the commercialization of the focal technology. Evidence from the recent emergence of the solar PV industry suggests that an entrant is more likely to choose a technology for which the complementary assets are available in the ecosystem than technologies for which they still need to be developed. As compared to de novo entrants, diversifying entrants are more likely to choose a technology for which complementary assets are available in the ecosystem. This difference between diversifying and de novo entrants is mostly due to diversifying entrants with capabilities that are specialized to the solar photovoltaic industry. The study argues that to understand the process of entry in a new industry, we need to explicitly consider the broader interaction between firm-level capabilities and ecosystem-level complementarities.

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Figure 1: Firm and Industry Trends during the Emergence of the Solar PV Industry

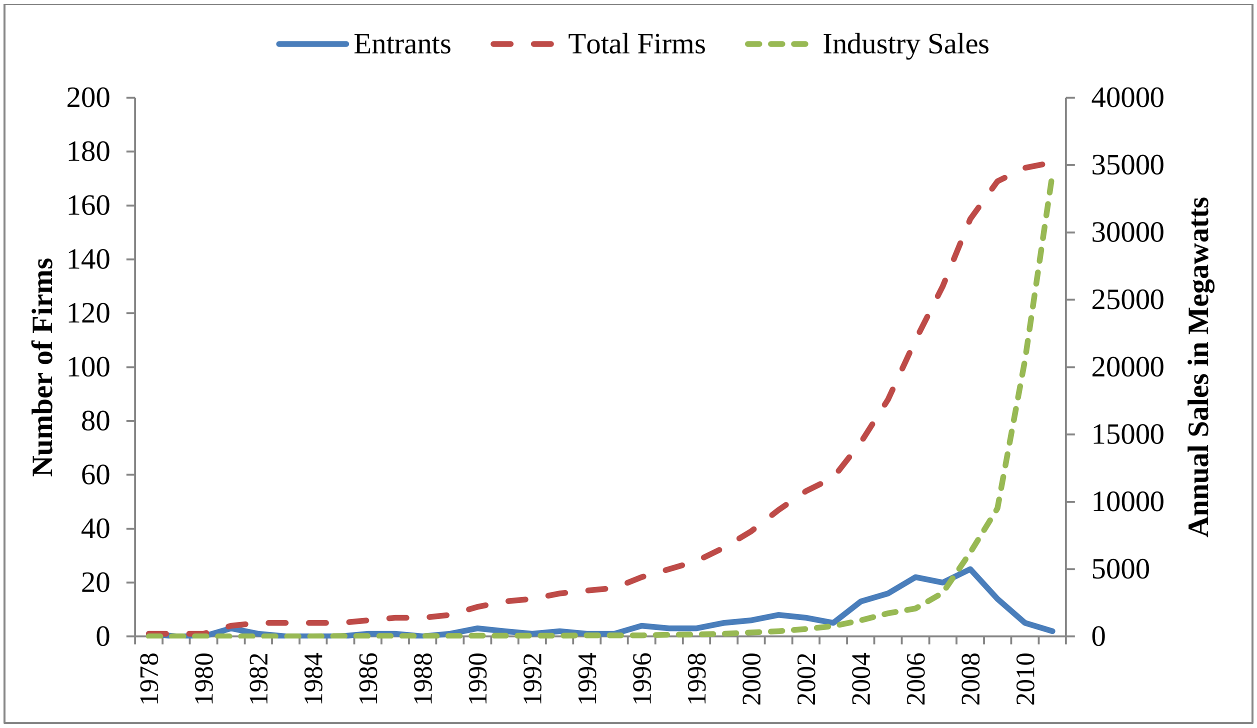

Figure 2: Number of Entrants by Technology by Year

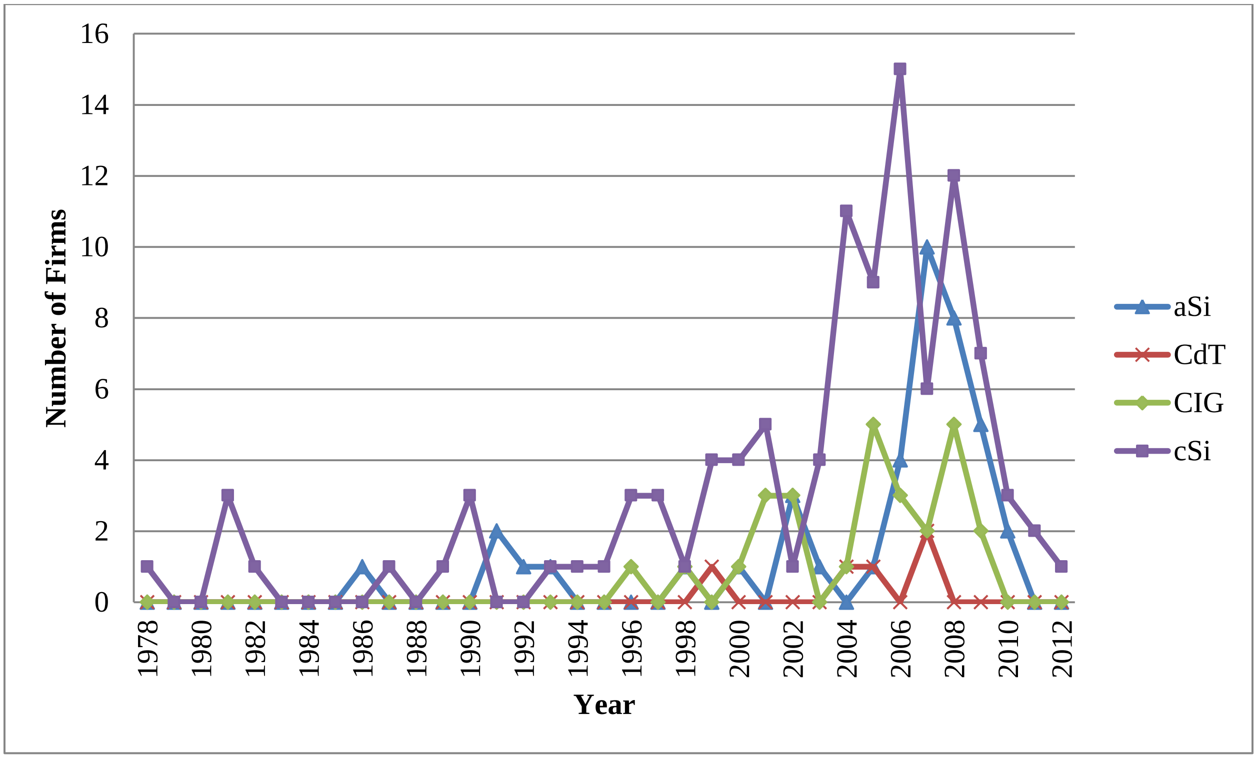

Table 1: Comparison of Solar Photovoltaic Technologies

PV Technology	Technology Characteristics*	Relative Efficiency	Relative Cost	Example Entrants
Crystalline Silicon (c-Si)	+ High efficiency - High material use (~200 micron wafer) - Many manufacturing stages	High	High	BP Solar, Samsung, Trina Solar
Amorphous Silicon (a-Si)	+ Low material use (<1 micron) + Higher energy absorption (low temp coeff.) - Low efficiency - Initial degradation (Staebler-Wronski effect)	Low	Low	Fuji Electric, Mitsubishi, Trony Solar
Cadmium Telluride (CdTe)	+ Low material use (3-5 microns) + Optimal absorption for solar spectrum - Perceived health risks (Cadmium)	Medium	Medium	First Solar, General Electric, Abound Solar
Copper Indium, Gallium, Di-Sellinide (CIGS)	+ Low material use (3-5 microns) + Long term stability + High-throughput manufacturing - Manufacturing complexity (four layer cell)	Medium-High	Medium-High	Solar Frontier, Honda, Nanosolar

* + indicates relative advantage and – indicates relative disadvantage.

Table 2: Classification of Diversifying Entrants' with Specialized and Generalized Pre-Entry Capabilities

Capability	NAICS Code Division	NAICS Code	NAICS Code Description	Rationale for Specialized Capability	Firm Count
Specialized	Manufacturing	3344	Semiconductor and Other Electronic Component Manufacturing	Semiconductor manufacturing related processes and integration capabilities	28
	Manufacturing	3341, 3342, 3343, 3359	Computer and Electronic Product Manufacturing; Communications Equipment Manufacturing; Electrical Equipment, Appliance, and Component Manufacturing	Semiconductor manufacturing related processes and integration capabilities	18
	Manufacturing	3332 (333242)	Semiconductor Machinery Manufacturing	Semiconductor manufacturing related processes and integration capabilities	2
	Construction	23*	Construction (Solar PV Installers Only)	Solar value chain capabilities	16
Generalized	Utilities	2211	Electric Power Generation, Transmission and Distribution		6
	Manufacturing	3241	Petroleum and Coal Products Manufacturing		2
	Manufacturing	3361, 3369	Motor Vehicle Manufacturing; Other Transportation Equipment Manufacturing		2
	Manufacturing	3252, 3323, 3141	Resin, Synthetic Rubber, Manf.; Metalworking Machinery Manf.; Textile Manf.; Plastics Manf.		8
	Manufacturing	3331, 3334, 3335	Agriculture, Construction, and Mining Machinery Manufacturing; Electrical Equipment Manufacturing; Metalworking Machinery Manufacturing		7
	Manufacturing	3272	Glass and Glass Product Manufacturing		4
	Manufacturing	3351	Electric Lighting Equipment Manufacturing;		3
	Finance / Management	5222, 5511	Nondepository Credit Intermediation; Management of Companies and Enterprises		4
	Wholesale Trade / Services	4236, 5614	Household Appliances and Electrical and Electronic Goods Merchant Wholesalers; Business Support		2

*An analysis by the National Renewable Energy Lab (2011) highlighted that a single solar PV downstream NAICS code does not exist. NREL's analysis suggests that the primary codes where solar PV downstream companies are found are: 236118 (Residential Remodelers), 238160 (Roofing Contractors), 238210 (Electrical Contractors and Other Wiring Installation Contractors), 238220 (Plumbing, Heating, and Air-Conditioning Contractors), and 238990 (All Other Specialty Trade Contractors). Therefore while we highlight the general category code of 23, we only include firms that actively engaged in downstream solar activities.

Table 3: Number of Entrants by Technology, Firm Type, and Pre-entry Capabilities

Technology	Total Entrants	De Novo Entrants	Diversifying Entrants	Diversifiers—Specialized Capabilities	Diversifiers—Generalized Capabilities
c-Si	103	38	65	51	14
a-Si	41	15	26	18	8
CdTe	5	4	1	1	0
CIGS	27	17	10	3	7

Table 4: Descriptive Statistics and Pairwise Correlation for Variables Used in the Regression Analysis

	Variable	Mean	Std. Dev.	Min	Max	1	2	3	4	5	6	7
1	Entry Choice	0.27	0.44	0.00	1.00							
2	Deposition	0.62	0.48	0.00	1.00	0.25*						
3	Contact	0.41	0.49	0.00	1.00	0.35*	0.65*					
4	Firm Count Tech	22.26	24.78	0.00	102.00	0.30*	0.50*	0.72*				
5	Tech Superiority	-1.07	0.47	-2.85	-0.60	-0.10*	-0.30*	-0.33*	-0.60*			
6	Tech Opportunity	1.09	0.07	1.00	1.34	-0.11*	-0.21*	-0.30*	-0.29*	0.06		
7	Annual Production	966.39	2727.77	0.00	30476.43	0.20*	0.26*	0.38*	0.74*	-0.35*	-0.25*	
8	Cumulative Production (Log)	2.35	1.25	-3.63	4.86	0.23*	0.65*	0.71*	0.74*	-0.37*	-0.15*	0.50*

* $p < 0.05$
Number of Observations = 653

Table 5: Conditional Logit Estimates of Entrants' Technology Choice in the Solar PV Industry

	(1) All Entrants	(2) All Entrants	(3) Diversifying	(4) De Novo	(5) Diversifying (Specialized)	(6) Diversifying (Generalized)
Deposition		0.351	1.306**	-0.658	2.171*	0.319
		(0.392)	(0.614)	(0.635)	(1.232)	(0.940)
Contact		1.134***	1.081**	1.431**	1.876***	-0.333
		(0.343)	(0.463)	(0.599)	(0.727)	(0.865)
Firm Count Tech	0.037***	0.025**	0.020	0.036**	0.006	0.078**
	(0.009)	(0.010)	(0.013)	(0.017)	(0.020)	(0.032)
Technical Superiority	0.877***	0.764***	0.592*	1.212***	0.475	0.034
	(0.240)	(0.258)	(0.332)	(0.450)	(0.461)	(0.711)
Technical Opportunity	-1.801	-0.988	2.327	-3.804	4.013	1.142
	(1.858)	(1.999)	(3.265)	(2.844)	(5.246)	(4.914)
Annual Production	-0.000	0.000	0.000	0.000	0.000	-0.001*
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Cumulative Production	0.130	-0.199	-0.100	-0.284	0.002	-0.092
	(0.120)	(0.150)	(0.263)	(0.195)	(0.365)	(0.511)
Log-likelihood	-183.45	-173.91	-88.65	-76.45	-45.49	-32.18
McFadden's pseudo-R2	0.19	0.23	0.33	0.18	0.50	0.21
Observations	648	648	379	269	262	117
Entrants	171	171	98	73	68	30

* p<0.1; ** p<0.05; *** p<0.01