

# COMPLEMENTARITIES AND COMPETITION: UNPACKING THE DRIVERS OF ENTRANTS' TECHNOLOGY CHOICES IN THE SOLAR PHOTOVOLTAIC INDUSTRY

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*Entrants in new industries pursue distinct technologies in hopes of winning the technology competition and achieving sustainable competitive advantage. We draw on the complementary assets framework to predict entrants' technology choices in an emerging industry. Evidence from the global solar photovoltaic industry supports our arguments that entrants are more likely to choose technologies with higher technical performance and for which key complementary assets are available in the ecosystem. However, diversifying entrants are more likely to trade off superior performance for complementary asset availability whereas start-up entrants are more likely to trade off complementary asset availability for superior performance. This difference is largely due to diversifying entrants with pre-entry capabilities related to the industry. The study offers a novel illustration of how complementarities and competition shape entry strategies.*

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## INTRODUCTION

The emergence of a new industry is characterized by a period of high uncertainty during which entrants pursue distinct technological alternatives in hopes of winning the technology competition and achieving sustainable competitive advantage (e.g., Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Suarez and Utterback, 1995). Hence, tied to a firm's entry into an emerging industry is the important decision as to the technology with which to enter that industry. Despite the strategic importance of this decision

towards an entrant's success in a new industry, we lack a systematic explanation for what drives the entrant's technology choice.

The complementary assets framework offered by Teece (1986) has been instrumental to our understanding of firms' entry strategies and performance outcomes. Strategy scholars have drawn on this framework to explain how the pre-entry asset base of a firm, such as its resources and capabilities in manufacturing, sales, marketing, and distribution, shapes its entry and performance in new industries (e.g., Helfat and Lieberman, 2002; Helfat and Raubitschek, 2000; Mitchell, 1989; Qian, Agarwal, and Hoetker, 2012). In doing so, the emphasis has been on the *redeployment* of firms' complementary resources and capabilities into new industries so as to appropriate value. Much less attention has been paid to the *availability* of complementary technologies and activities in the ecosystem that are necessary for firms to

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create value in the new industry in the first place (Adner and Kapoor, 2010; Teece, 2006).<sup>1</sup> Hence, by focusing primarily on the redeployability of firms' complementary capabilities, the literature provides limited treatment of the complementarities that underlie firms' entry strategies, including incomplete insight into the entry strategies of start-up entrants that lack pre-entry capabilities.

In this study, we unpack the drivers of entrants' technology choices in an emerging industry by considering the role of both firm-level and ecosystem-level complementarities. To do so, we characterize the different technology choices according to their core technical performance and the availability of complementary assets in the ecosystem.<sup>2</sup> For example, the early automobile industry was populated by entrants competing via steam, electric, or internal combustion engine technologies. These technologies not only differed in their core technical performance but also in the extent to which complementary assets such as the manufacturing equipment for mass production and key technological components were available in the ecosystem (Kimes, 2004). Hence, entrants may need to make a trade-off with respect to the technology's core performance and the availability of complementary assets. We argue that the relative importance of technical performance and the availability of complementary assets towards an entrant's technology choice will depend on the entrants' prehistory: diversifying entrants who bring capabilities from other industries may consider this trade-off differently than start-ups founded to participate in the industry. We also consider how the technology choice may be impacted by whether diversifying entrants' capabilities and start-ups' founder experience are related or unrelated to the new industry (Helfat and Lieberman, 2002).

We explore our arguments in the context of the global solar photovoltaic (PV) industry from the late 1970s to 2011. With the emphasis on the

renewable energy sector, the industry has been gaining in importance over the last two decades. 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 study period, we observe both diversifying firms and start-ups entering the industry and pursuing four distinct technological choices with no clear consensus regarding which technology will become the dominant design (Ardani and Margolis, 2011; Chopra, Paulson, and Dutta, 2004; Peters *et al.*, 2011).

We find that an entrant into the solar PV industry is more likely to choose a technology with higher technical performance and for which the key complementary assets are available in the ecosystem. However, the relative importance of technical performance and availability of complementary assets towards an entrant's technology choice is contingent on its pre-entry characteristics. Diversifying entrants seeking to leverage pre-entry capabilities are more likely to trade off superior technical performance for the availability of complementary assets, whereas start-up entrants seeking to differentiate from those diversifiers are more likely to trade off the availability of complementary assets for superior technical performance. This difference between diversifying and start-up entrants is largely due to diversifying entrants with pre-entry capabilities that are related to the solar PV industry. While the evidence is not conclusive, start-ups with unrelated founder experience seem to place greater emphasis on technical performance than do start-ups with related founder experience.

These findings show how a broader treatment of complementarities that considers both firm-level capabilities and ecosystem-level interdependencies can offer new insights regarding how firms compete and create value in emerging industries. Interdependencies in the ecosystem are becoming increasingly prevalent as technologies are becoming more complex and firms more specialized (e.g., Adner, 2012; Iansiti and Levien, 2004). While strategy scholars have successfully drawn on the complementary assets framework (Teece, 1986) to explain firms' entry strategies and performance outcomes, the predominant emphasis has been on the redeployment of firms' complementary resources and capabilities into new markets so as to appropriate value rather than on the availability of complementary technologies and activities

<sup>1</sup>The term complementary assets is an umbrella term that is used to identify the different types of complementary resources, capabilities, technologies, and activities that are required for the commercialization of a given core technology (Teece, 2006).

<sup>2</sup>Availability of complementary assets in the study refers to the fact that the key assets required for commercialization of a given technology can be easily accessed through the markets with little modification. The opposite scenario is that complementary assets require significant development, either by focal firms themselves or in collaboration with external partners (Adner and Kapoor, 2010; Teece, 2006; Winter, 2006).

in the ecosystem that are necessary for value creation in new markets (e.g., Priem, Butler, and Li, 2013; Teece, 2006).

The characterization of technology choices along the dimension of complementary assets availability in addition to the typical dimension of core technical performance sheds light on a key trade-off facing entrants in an emerging industry. Certain technologies may have higher performance but may lack the necessary complementary assets, resulting in commercialization challenges, while other technologies may have lower performance but have easily accessible complementary assets that allow the entrant to readily participate in a growing industry. Considering this trade-off through the lens of firms' pre-entry capabilities allows us to explain why competition between diversifying entrants and start-ups may lead them to pursue different technology choices. In doing so, we also illustrate an important but previously unexamined linkage between the technology management perspective of industry evolution, which emphasizes entrants' technological diversity (e.g., Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Suarez and Utterback, 1995), and the evolutionary economics perspective that underscores firms' pre-entry heterogeneity (e.g., Ganco and Agarwal, 2009; Klepper and Simons, 2000). Finally, the evidence from the solar PV industry demonstrates the benefits of a finer categorization of firms' pre-entry capabilities and start-ups' founder experience with respect to the relatedness to the focal industry (Helfat and Lieberman, 2002).

## LITERATURE REVIEW AND HYPOTHESES

Strategy scholars have studied the process of entry into 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; Christensen, Suarez, and Utterback, 1998; 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 technological diversity during the growth stage of an industry, no attempt has been made to uncover why firms choose different technologies at entry.

By contrast, scholars grounded in evolutionary economics have viewed entry through the lens of firms' pre-entry capabilities and have shown that pre-entry capability differences between diversifying and start-up entrants have an important bearing on their performance outcomes (Ganco and Agarwal, 2009; Helfat and Lieberman, 2002; Khessina and Carroll, 2008; Klepper, 2002; Klepper and Simons, 2000). However, while this literature stream has generated useful insights regarding the relationship between firms' pre-entry capabilities and performance outcomes, it has tended to underemphasize the differences in the strategies pursued by entrants in order to compete in an emerging industry. A notable exception is the study by Qian *et al.* (2012) in which the authors explore the sources of differences in entrants' vertical integration choices in the U.S. bioethanol industry.

In this study, we develop a framework that predicts entrants' technology choices in an emerging industry by considering such choices in terms of core technical performance and the complementary assets that underlie a given technology's commercialization. Empirical examinations of the role of complementary assets in firms' entry decisions have focused on the redeployment of their complementary 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 that they could redeploy into new markets. 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. Helfat and Lieberman (2002) offer a valuable synthesis of the literature and reinforce the importance of firms' resources and capabilities to their entry choices and performance outcomes.

While the bulk of attention has been devoted to firms' complementary capabilities, complementary assets also reside in the external business ecosystem that encompasses interdependent technologies

and activities (Adner and Kapoor, 2010; Teece, 2006). Such complementary assets may play a critical, but as yet unexamined, role in firms' entry decisions. As Teece (2006) notes in his reflection on his seminal article, the treatment of complementarities in the article was somewhat limited. The article, while acknowledging the systemic nature of a technology, focused much more on the firm-level value chain (pp. 1138–1139). In so doing, it tended to downplay the importance of technological complementarities in the ecosystem that can be a bottleneck to value creation by the focal technology. For example, successful commercialization of electric cars depends on the availability of batteries with high charging density and low cost as well as the availability of the charging infrastructure. Similarly, commercialization of new generations of semiconductor chips does not solely depend on a new chip design but also on the availability of equipment for mass manufacturing of miniaturized circuits (Kapoor and Adner, 2012). Such technological interdependencies have been documented by historians in the context of aircraft engines (Constant, 1980), machine tools (Rosenberg, 1963), and electricity networks (Hughes, 1983), and have only recently been examined in the strategy literature (Adner and Kapoor, 2010).

We explicitly consider firms' technology entry choices in an emerging industry through both their ability to redeploy complementary capabilities and the availability of complementary assets in the ecosystem. First, we characterize the different technological choices according to their core technical performance (i.e., the performance of the focal technology with respect to key technical attribute[s]) and the availability of complementary assets. Then, we identify how these technological characteristics may interact with firms' pre-entry capabilities to shape their entry choice.

The emergence of a new industry is typified by a period of intense experimentation and learning, with multiple competing technologies and no consensus concerning the dominant design. Technological variation during this stage represents different solutions to addressing the needs of the users. Because of high technological uncertainty and opportunity, the relative performance superiority of a given technology evolves over time (Anderson and Tushman, 1990; Garud and Karnøe, 2003). Although the best performing technology may not always win and become the dominant design, at the time of entry, entrants may still

be more likely to prefer higher performing technologies in the hope of creating a competitive advantage. Therefore, as a baseline expectation, we predict:

*Hypothesis 1: An entrant is more likely to choose a technology with superior core technical performance.*

In addition to core technical performance, technologies within an emerging industry may also differ in the extent to which the necessary complementary assets are available in the ecosystem. This is because the different technological solutions arise from evolutionary speciation events that entail adaptation and recombination of technological knowledge from existing application domains towards new application domains (Adner and Levinthal, 2002; Levinthal, 1998). Some of these innovative solutions may be able to readily draw on complementary assets that exist in other industries and, thus, while they may be new to the application domain, they are not new to the world. In such a case, complementary assets may be transferred into and adapted into the industry. In contrast, other technologies may require new-to-the-world complementary assets and thus demand significant development of or modification to the complementary assets before the technology's commercialization potential can be fully realized (Adner and Kapoor, 2010; Teece, 2006).

For example, the emergence of the automobile industry was characterized by significant technological diversity, with entrants pursuing steam, electric, and internal combustion engine technologies in the competition for industry dominance. These technologies differed not only in the core technical performance but also in the extent to which some of the key complementary assets were available (Kimes, 2004). Steam engine components and manufacturing equipment had been used in the production of locomotives and ships, and modifying them for use in the automobile industry was relatively easy. Similarly, some of the key components of internal combustion engines became readily available as the broader market for combustion engines evolved. In contrast, although several entrants attempted electric vehicles, which were cleaner, quieter, and more popular than internal combustion designs, the commercialization of electric vehicles required

significant development in components such as batteries and electric motors.

When faced with multiple competing technologies that differ in the availability of complementary assets, entrants may be more likely to choose technologies for which the complementary assets are readily available in the ecosystem. Developing complementary assets specific to a new industry can be costly and uncertain, sometimes 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 technology-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 (Dierickx and Cool, 1989). If complementary assets are available in the ecosystem for a given technology, entrants face lower commercialization challenges and can readily participate in a growing industry. They can then compete based on their superior capabilities and learning curve efficiencies. Therefore, in an emerging industry with competing technologies, entrants will be 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 challenge and leverage the opportunities in the growing industry. Hence, in addition to choosing a technology with superior performance, as a second baseline prediction, we expect that an entrant will choose a technology for which the key complementary assets are available:

*Hypothesis 2: An entrant is more likely to choose a technology for which the key complementary assets within the ecosystem are available than a technology for which they need to be developed.*

The existence of multiple competing technologies during the emergent stage of an industry is often referred to as an era of ferment, during which technology's performance profiles are highly uncertain. Not only do technologies vary in their relative performance advantage over time, they also differ in the extent to which the necessary complementary assets are available. Given the

evolutionary nature of technological advance, with nonuniform performance trajectories, it is highly likely that potential entrants would face a trade-off with respect to a given technology's performance superiority and the availability of complementary assets (e.g., Anderson and Tushman, 1990; Wu, Wan, and Levinthal, 2013). We view this trade-off through the lens of firms' pre-entry history.<sup>3</sup>

Pre-entry experience and capabilities are an important source of heterogeneity among industry entrants (Helfat and Lieberman, 2002). Entrants could be established firms that are diversifying from their existing industries and redeploying their capabilities into the new industry or start-ups that are founded to participate in the new industry. While the literature has often accorded diversifying entrants with pre-entry capabilities, start-ups' founders also have a pre-entry history that may impact their entry choice (Agarwal *et al.*, 2004; Klepper, 2002). For example, founders of start-ups may have the relevant technical and market experience required to compete in the new industry (Furr, Cavarretta, and Garg, 2012; Klepper, 2001). However, start-ups lack organizational capabilities and therefore must develop them upon entry (Chen, Williams, and Agarwal, 2012; Qian *et al.*, 2012). Hence, entry by diversifying firms is premised on capability redeployment and adaptation of the capability to a new industry, whereas entry by start-ups is premised on capability development and the initiation of their capability life cycle (Helfat and Eisenhardt, 2005; Helfat and Peteraf, 2003). This difference between diversifying firms possessing and seeking to redeploy organizational capabilities and start-ups who must develop organization-level capabilities may alter entrants' incentives with respect to technology choices.

When complementary assets are available in the ecosystem for a given technology, these technologies face no significant bottleneck to commercialization. Although all entrants may prefer technologies with available complementary assets,

<sup>3</sup>Note that we are not assuming that the higher the performance of a given technology, the lower the availability of complementary assets. It is often the case that new technologies with superior technical performance may or may not have complementary assets available at the time of emergence, or competing technologies may witness unexpected improvement or stagnation in their performance profiles over time. We do observe in our context that some high-performing technologies emerged with available complementary assets whereas others did not and that competing technologies witnessed significant shifts in their relative performance superiority over time.

diversifying firms may be better positioned to leverage these assets to establish an advantage over start-up entrants. While diversifying entrants may have to adapt their existing complementary capabilities to compete in the new industry, much of the necessary costs of capability development have already been incurred, in contrast to start-up entrants who must first develop these capabilities. This is particularly true for integrative capabilities, defined as the knowledge of how to integrate activities, capabilities, and products (Chen *et al.*, 2012; Helfat and Raubitschek, 2000). Hence, by leveraging their existing stock of complementary capabilities, diversifying entrants will be able to achieve faster commercialization by choosing technologies for which complementary assets are readily available, and go down the learning curve (Lieberman and Montgomery, 1998). In an era of ferment with multiple competing technologies, early advances in commercialization could also provide diversifying entrants with a competitive edge in establishing the dominant design, even if the technology they choose lacks performance superiority (Anderson and Tushman, 1990; Tushman and Rosenkopf, 1992; Utterback, 1996). Hence, while all entrants would prefer technologies with both high performance and available complementary assets, diversifying entrants will be more likely to trade off technical performance for the availability of complementary assets when making their entry choice.

Wu *et al.* (2013) discuss a similar trade-off in the context of technological discontinuities. Using a formal model, they show that, compared to start-up entrants, established incumbents will be more likely to pursue technologies with lower technical performance but that allow them to leverage their existing complementary resources and capabilities. They offer an interesting analogy with respect to established firms' complementary capabilities, characterizing their dual role as pipes that act as an isolating mechanism from competitors, and prisms, which shape perceptions about which technologies offer greater opportunities for value appropriation.

By contrast, because start-up entrants lack organizational capabilities at entry, when complementary assets are available for a given technology, start-ups' ability to compete against diversifying entrants within that technology will be limited as start-ups still have to accumulate organizational capabilities. Hence, as compared to a diversifying entrant, a start-up may seek to differentiate from diversifiers by choosing high-performing

technologies lacking complementary assets. Even though such a choice will require greater levels of investment, it offers the start-up an opportunity to accumulate specialized complementary capabilities with a superior technology. Higher performing technology could create greater value, and the development of specialized complementary capabilities will allow the start-up to also appropriate value in a sustained manner (Dierickx and Cool, 1989; Helfat and Peteraf, 2003; Teece, 2006). Therefore, although the choice to pursue a high-performing technology that lacks complementary assets *ex ante* may be more costly, it may still be a more viable choice for start-ups to differentiate from diversifying entrants with pre-entry capabilities.

In summary, we expect that, while diversifying entrants would be more likely to trade off core technical performance for the availability of complementary assets, start-ups would be more likely to trade off the availability of complementary assets for core technical performance.

*Hypothesis 3: Relative to core technical performance, availability of complementary assets will have a greater effect on the technology choice of diversifying entrants than that of start-up entrants.*

We next consider how diversifying entrants' preference for technologies with available complementary assets varies by the type of their pre-entry capabilities. While all diversifying entrants have a stock of pre-entry organizational capabilities, they may differ in the degree to which their capabilities match those required for technology commercialization in the new industry (Helfat and Lieberman, 2002). For example, diversifiers may have related capabilities that directly facilitate commercialization of technology into the new industry (e.g., manufacturing, distribution, marketing, customer relationships, etc.) or those that are less directly related to the industry (e.g., corporate-level capability of managing multiple businesses, facilitating knowledge transfer, etc.).

The smaller the relatedness gap between the firms' pre-entry capabilities and those required for the technology's commercialization, the lower the firms' cost to adapt and redeploy their existing capabilities to compete in the new industry. Hence, possessing related rather than unrelated

pre-entry capabilities lowers the cost of developing the full portfolio of capabilities necessary for successful technology commercialization (Helfat and Peteraf, 2003; Helfat and Raubitschek, 2000). If there are no bottlenecks in the ecosystem in terms of the technology's value creation (i.e., complementary assets are available), diversifying firms with related pre-entry capabilities can even more readily leverage their capabilities to achieve faster commercialization, go down the learning curve, and increase their chances of winning the technology competition than can diversifying firms with unrelated pre-entry capabilities.

By contrast, diversifying entrants with unrelated pre-entry capabilities may recognize that they are at a disadvantage relative to diversifiers with related pre-entry capabilities when complementary assets are available. Therefore, they may pursue strategies that would allow them to create an advantage over diversifying entrants with related pre-entry capabilities. By placing greater emphasis on a technology's performance than the availability of complementary assets, they would be able to invest in and accumulate capabilities within a superior technology so as to effectively compete. Hence, the availability of complementary assets towards diversifying entrants' technology choices will have a greater effect on those entrants with related pre-entry capabilities than those with unrelated pre-entry capabilities:

*Hypothesis 4: The availability of complementary assets will have a greater effect on diversifying entrant's technology choice for those entrants with related pre-entry capabilities than those entrants with unrelated pre-entry capabilities.*

Finally, we consider how start-up entrants' preference for technologies with superior technical performance varies for start-ups with different types of founder experience. Just as diversifying entrants differ in the extent to which their capabilities match those required for competing in the new industry, founders of start-ups also differ in the extent that their prior experience facilitates technology commercialization in the new industry (Furr *et al.*, 2012; Shane, 2000). Founders' prior experience has been shown to play an important role in their firms' entry strategies (Bingham, Eisenhardt, and Furr, 2007; Eisenhardt and Schoonhoven, 1996; Fern, Cardinal, and O'Neill,

2012). Founders with experience directly related to the technology's commercialization will be more likely to see opportunities to leverage their experience in combination with complementary assets to readily participate in the growing industry (Ozcan and Eisenhardt, 2009). For example, founders with related manufacturing know-how or customer relationships may be more willing to choose technologies that do not face any significant bottlenecks in the ecosystem. In contrast, founders with unrelated experience have the burden of being the most distant in terms of experience and capabilities that underlie the technology's commercialization in the new industry. As a result, in their quest to develop superior organizational capabilities and compete effectively, they may place greater emphasis on the technology's performance superiority. Hence, we propose that:

*Hypothesis 5: Core technical performance will have a greater effect on start-up entrant's technology choice for those start-ups with unrelated founder experience than those start-ups with related founder experience.*

## RESEARCH CONTEXT

We explore our arguments in the context of the global solar PV industry during its period of emergence from 1978 to 2011. The industry has been one of the most important pillars of the renewable energy sector. In addition to the economic and policy prominence, it 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 diversifiers and start-ups, pursued four distinct technological choices with no consensus in the industry as to which technology would be the dominant design (Chopra *et al.*, 2004; Peters *et al.*, 2011). The four technologies differ in both their performance trajectories and in the extent to which the complementary assets were available to facilitate commercialization upon entry. 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, 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 industry, the different types of technologies pursued by entrants, the nature of complementary assets, and the factors influencing entrants' technology choices. We interviewed over 30 industry professionals, which included employees of solar PV firms, industry analysts/consultants, and solar PV scientists, as well as conducted several visits to solar PV module manufacturing plants, research labs, and industry conferences. These interviews and visits entailed semi-structured interviews based on an interview guide, lasting from an average of 1.5 hours to full-day site visits. Finally, we conducted a thorough review of the two most comprehensive industry trade journals: *PV News* and *Photon International*.

For the quantitative analysis, we drew on the proprietary industry database maintained by Greentech Media ([www.greentechmedia.com](http://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 have competed in the industry since its beginnings. We gathered self-reported data on firms' entry years, their technology choices, and pre-entry characteristics from company websites, public filings, and through personal communication. We then corroborated these data with 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* (the leading peer-reviewed academic journal dedicated to advancements in solar PV technology), *Photon International*, and the U.S. Department of Energy's National Renewable Energies Lab.

## Industry background

Firms in the solar PV industry manufacture solar PV modules that 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, thus generating electric current. The materials in commercial use include crystalline silicon, amorphous silicon, cadmium telluride, and CIGS (copper indium gallium di-selenide).

The first terrestrial solar PV module was developed in 1955 by Bell Labs and was soon followed by several mostly failed attempts to commercially produce PV modules 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 entry of several firms attempting to commercialize solar PV modules (Bradford, 2006). 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 concerns led to new policies that reinvigorated the solar industry and saw a significant increase in the number of entrants. 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. Figure 1 depicts the pattern of entry into the solar PV industry. The observed entry pattern 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).

## Entrants' technology choices

Entrants into the industry pursued four distinct technology choices (see Figure 2). Underlying these technology choices was the selection of the material used to convert energy from sunlight into electricity. 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 (which are first produced by growing a silicon ingot of high purity in a quartz crucible, slicing the ingot into wafers, and then doping and

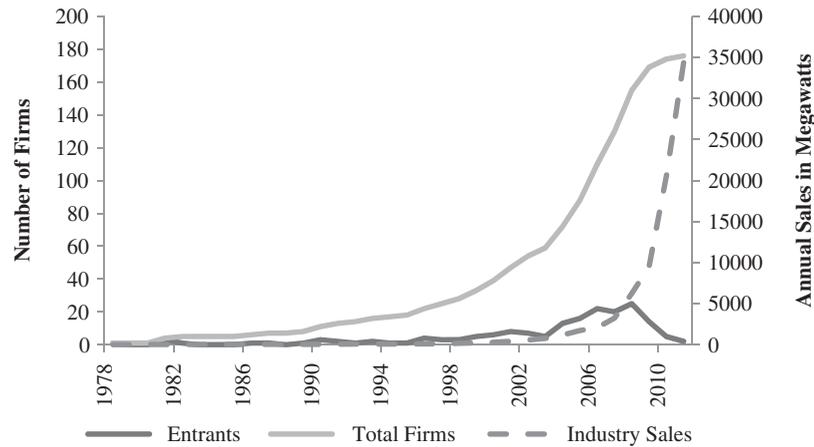


Figure 1. Industry trends during the emergence of the global solar PV industry

processing wafers into cells). Because c-Si has a highly ordered atomic structure, these modules offer the highest efficiency (meaning they convert the highest percentage of sunlight into electricity), but they are also of higher cost due to the many processing steps and the large quantity of semiconductor material used (often, c-Si cells are 200–300 microns ( $10^{-6}$  m) thick, whereas the semiconductor material in other technologies is less than 10 microns thick).

Amorphous-silicon (a-Si), unstructured silicon with very different atomic properties from those of c-Si, emerged as a commercial alternative in the 1980s. It can be sprayed in a thin layer (<1 micron) onto a substrate and manufactured much more quickly, yielding the lowest production costs but also the lowest efficiency of all solar PV modules. Somewhat less emphasized, a-Si has better absorption of mid-day sun and a lower temperature coefficient, which offers

more resilience to temperature fluctuations but tends to degrade slightly after initial exposure to light.

CIGS technology, an abbreviation for the semiconductor materials in this four-layer module (copper, indium, gallium, di-selenide), emerged as a commercial alternative in the mid-1990s. CIGS offers the benefits of high sunlight conversion efficiencies (research cell efficiencies approaching those of crystalline silicon) and low material use (3–5 microns of semiconductor material). However, CIGS also has a higher cost than amorphous silicon because of the four-layer module, which includes the rare-earth element indium.

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) and moderate cost. As a minor consideration, CdTe has battled perceptions

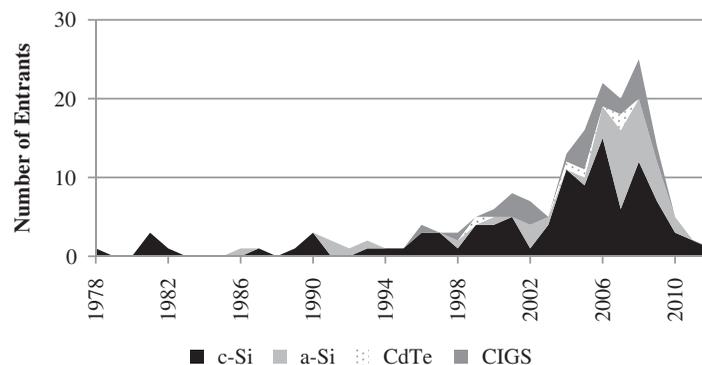


Figure 2. Number of entrants by technology by year

about cadmium toxicity, in response to which manufacturers have developed recycling programs.

Which of the four technologies will become the dominant design has remained a question of significant debate within the industry (Bradford, 2006; Chopra *et al.*, 2004; Peters *et al.*, 2011). Over the period of study, each of the technologies witnessed significant improvements in performance. However, the pattern of these improvements differed across technologies, over time leading to shifts in the technologies' relative performance superiority. Every technology was chosen and developed by both major diversifying firms (BP, GE, Mitsubishi, Honda, etc.) as well as keenly followed start-ups (First Solar, Solar Frontier, Trony Solar, Trina Solar, etc.). 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 *Progress in Photovoltaics*, Peters *et al.* (2011) conclude that "it is unclear which solar technology is and will prove most viable."

### Complementary assets in the ecosystem

The core know-how for solar PV module technology needs to be combined with complementary assets for entrants to create value through commercialization. While diversifying entrants were endowed with complementary capabilities such as those in manufacturing, marketing, and distribution, all entrants required solar PV manufacturing equipment—expensive and complex manufacturing equipment with significant embedded technology-specific knowledge—to mass produce solar PV modules. There are several types of manufacturing equipment specialized to a given technology that play a particularly significant role in a firm's ability to commercialize PV modules. The most important among these are (1) the deposition equipment that deposits the semiconductor layers for the solar cell, and (2) the contact equipment that creates the conductive grid that carries current from the individual cells to the modules' external electrical connections (Papathanasiou, 2009; Richard, 2010).<sup>4</sup> These

pieces of equipment are technologically complex, and their development represent large investments of intellectual and financial capital.

The availability of the deposition and contact equipment differed dramatically between technologies. C-Si benefited from spillovers from the 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 becoming available in 1994. Similarly, the manufacturing equipment for a-Si 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 laboratory and production efficiencies than a-Si), commercial manufacturing equipment was not available until 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 equipment and knowledge used 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 P. 2013. Personal Interview). As a result of these challenges, the deposition equipment for CIGS was not commercially available until 2007 and, although contact equipment appeared one year later, only a single model was offered. For CdTe, deposition equipment was not available until 2011, and contact equipment has been promised but little has been delivered.

Entrants pursuing technologies for which the deposition and contact equipment were not commercially available had to develop their own

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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.

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<sup>4</sup>Note that while there are many different types of downstream complementary assets within the solar PV industry such as

equipment, often by modifying equipment from another industry. Such developments represented intensive capital and technical investments. As an illustration of the scale and the complexity of the manufacturing equipment, the contact equipment produced by FHR/Centrotherm for the CIGS PV module is 33 m in length, weighs 130 tons, and is sold for more than US \$9 million (Papathanasiou, 2009). When speaking about the need 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 C. 2007. Personal Interview). Despite these challenges, given the technical and economic potential, many entrants did invest in developing equipment for these technologies in pursuit of a competitive advantage. To rationalize the adoption of 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” (Atluru R. 2007. Personal Interview).

## EMPIRICAL ANALYSIS

### Dependent variable

Our hypotheses predict entrants’ technology choice in an emerging industry. The dependent variable, *entry choice*, is a binary variable equal to 1 for the solar PV technology with which a firm chose to enter the industry, and 0 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. Twelve 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 broaden their technology portfolio given the pervasive uncertainty about which technology might become the dominant design.

### Independent variables

Testing of hypotheses required a measure of a given technology’s technical performance that is comparable across technologies and over time. An attractive feature of the solar PV industry for the purpose of our study is that cost per watt (CPW)

has been established as the standard measure for comparing performance across technologies and over time (Bradford, 2006). CPW is used because different technologies have different efficiencies but also different costs; therefore, direct comparison of technologies by efficiency alone is imperfect (i.e., c-Si has high efficiency but high cost of materials whereas a-Si has low efficiency but low cost). Hence, CPW captures both the cost and efficiency differences between technologies.

Because historical CPW data is unavailable, we employ a standard approach used by industry analysts to measure *technology performance* by explicitly considering changes in both the efficiency and cost (e.g., Grama and Bradford, 2008; Mehta, 2010). Specifically, we use CPW data for the final year of the sample, as reported by Greentech Media (Mehta, 2010), as a baseline and then adjust the performance measure based on historical changes in efficiency and costs of materials. While changes in efficiency have been the primary driver of changes in performance for all of the four technology choices, changes in the cost of materials have primarily affected the performance of c-Si technology, which has high materials consumption and has witnessed major fluctuations in the price of raw silicon. We operationalize a given technology’s performance in year  $t$  ( $CPW_t$ ) using the following formula:

$$CPW_t = CPW_{2011} \times \text{Cost Ratio}_t \\ \times \text{Efficiency}_{2011} / \text{Efficiency}_t,$$

where  $\text{Cost Ratio}_t$  is the ratio of average price of silicon in year  $t$  to that in year 2011 for c-Si technology and assumed to be 1 for the other technologies (other technologies have very low material consumption and did not experience significant changes in the cost of materials). For ease of interpretation, we invert the sign so the measure takes negative values, thus a higher value implies higher performance of the technology. The hypothesized effects were robust to only using efficiency as a measure of core technical performance without adjusting for differences in costs, albeit with poorer model fit.

The availability of complementary assets is operationalized based on the commercial availability of the deposition and contact manufacturing equipment. The time frame for the commercial availability of equipment is identified based on

the equipment suppliers' self-reported information in the *Photon International* annual equipment surveys as well as their product specifications. The variable, *complementary assets*, takes a value of 2 if both the deposition and contact equipment were commercially available for a given technology prior to the year of entry, a value of 1 if either of the deposition or contact equipment were commercially available, and 0 if none of the deposition or contact equipment were commercially available. In almost all instances, the commercial availability implied that the deposition and contact manufacturing equipment were being offered by at least three suppliers. The only exception was the deposition equipment for CdTe from 2008 to 2011 when the equipment was offered by only one supplier. As a robustness check, we code these years as the years in which the deposition equipment for CdTe was unavailable and found the results to be nearly identical. Some solar PV module entrants using c-Si technology did not manufacture solar cells themselves but procured them from suppliers of semiconductor materials. Hence, these entrants did not require deposition equipment.<sup>5</sup> As additional robustness checks, which we present after our main results, we exclude these entrants from the analysis and also test only for the effect of the contact equipment availability.

Testing of Hypothesis 3 required that we categorize firms into diversifying and start-up 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 as a start-up otherwise.<sup>6</sup> Finally,

<sup>5</sup>Note that within the complementary assets framework, solar cells are a key complementary asset for the solar PV module entrant who does not manufacture the cells themselves (e.g., Teece's, 2006, example of batteries for electric cars). Just as the deposition equipment for c-Si was commercially available very early in the industry (1984), so too solar cells have been commercially available since the late 1970s. Hence, regardless of the PV module entrant's choice to manufacture c-Si solar cells or not, availability of the key complementary asset related to c-Si solar cells would be coded as 1 throughout the period of study.

<sup>6</sup>We note that while categorizing entrants into diversifying and start-up entrants represents a dominant categorization schema in the literature, scholars have also identified two other types of entrants—spinouts and incumbent-backed ventures (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 ventures, subsidiaries) to the incumbents. Hence, spinout is a subcategory of start-up entrants, and incumbent-backed ventures

testing of Hypotheses 4 and 5 entailed classifying diversifying entrants' pre-entry capabilities and start-up founders' experience into related and unrelated categories. To classify diversifiers' pre-entry capabilities, we identify 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 codes, and following Helfat and Lieberman (2002), we categorize each diversifying entrant as having pre-entry capabilities that were either related or unrelated to the commercialization of solar PV module technology. Related capabilities include semiconductor manufacturing capabilities as well as marketing and distribution capabilities related to the solar PV industry (e.g., customer relationships, understanding of customer preferences). Similarly, for start-ups, we examine the background of the founder(s) and classify start-up entrants based on whether the founders' primary industry background was in related or unrelated industries based on the NAICS description.<sup>7</sup> We discussed the concordance between NAICS classification and our related vs. unrelated categorization with solar PV industry experts who agreed unanimously with our categorization. Table S1 in the online Supporting Information summarizes the concordance between NAICS classification and entrants' background, and our corresponding rationale.<sup>8</sup> Figure 3 plots the trend in the number of different types of solar

represent a hybrid between start-up and diversifying entrants. Because we are focusing on the emergence period of the industry, spinouts and incumbent-backed firms represented a small proportion of our sample (12%). For our main analysis, we classify these firms as start-up entrants. We conducted supplementary analyses in which we first exclude them from the sample and then treat the hybrid incumbent-backed entrants as diversifying entrant and spin-outs as start-ups. The results are robust to these analyses.

<sup>7</sup>Nineteen of the start-ups had founders with primary background in solar PV research (a majority of them had worked at university laboratories). These start-ups pursued all four technology choices. Because their founders have core technological know-how but lack experience in complementary activities that underlie solar PV module commercialization, their start-ups, within our commercialization-oriented schema, were categorized as those with unrelated founder experience. As a robustness check, we conducted an analysis in which we categorized these start-ups as related. While the results for the related category were similar to our main results, because of the very small sample size, the coefficient estimates for the technology performance and complementary assets variables within the unrelated category were insignificant ( $p = 0.18$ ;  $p = 0.15$ ).

<sup>8</sup>Although it may appear that entrants and founders from some manufacturing industries (e.g., automotive) might have capabilities and experience applicable to manufacturing solar PV, given

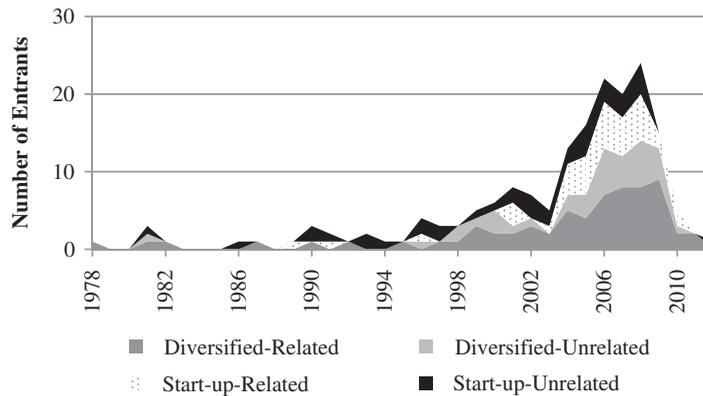


Figure 3. Number of entrants by background by year

PV module entrants. Out of 176 entrants, 66 are diversifying entrants with related capabilities, 36 are diversifying entrants with unrelated capabilities, 37 are start-ups with related founder experience, and 37 are start-ups with unrelated founder experience.

### Control variables

We include a number of technology-specific controls. An entrant's technology choice may be affected by the number of firms that are in a given technology at the time of entry. We include a variable, *firm count*, to account for this effect. To control for the relative market dominance of these technologies, we include the 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, i.e., 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. In order to control for the technology-level maturity and learning curve effects, we include a control variable, *cumulative production*, which is the logarithm of the cumulative production in megawatts for a given technology in the year of entry. As an alternative

measure for technology maturity, we also experiment with the number of years since the technology was first commercialized and find the results to be very similar. We include a control variable, *annual growth*, measured as the percentage year-over-year change in megawatts sold for a given technology. Finally, an entrant's technology choice may be influenced not only by the technology's existing performance but also by its future potential for performance improvement, particularly as it relates to improvements in efficiency. To control for this effect, we employ the variable, *technical opportunity*, measured as the ratio of highest available production efficiency available after three years to the highest available production efficiency available in the current year. We also explore an alternate measure based on the ratio of the NREL recorded research efficiency (highest efficiency achieved in a research lab) to the highest available production efficiency in a given year. These measures produce similar estimates without qualitatively changing the results for the hypothesized effects.

### Model

Each entrant chooses one technology among the set of available technology alternatives. Our arguments assume that an entrant chooses the technology that offers 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' strategic decision making with multiple alternatives (Fern *et al.*, 2012; Greve, 2000; Hoetker,

the specialized technical nature of mass manufacturing of semiconductor devices, solar experts confirmed our assessment that we should classify those firms and founders as having unrelated pre-entry capabilities and experience, respectively.

2006; Kalnins and Chung, 2004; 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  $i$  derives from choosing technology  $j$  is

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

where  $\beta'$  is the vector of coefficients to be estimated and  $\varepsilon_{ij}$  is an unobserved random term reflecting unobserved heterogeneity in entrants' decision making. The conditional logit model estimates the probability that an entrant  $i$  chooses technology  $j$  among  $n$  choices. The probability function is given by

$$\text{Prob}(Y_i = j) = \frac{\exp(\beta' \mathbf{X}_{ij})}{\sum_{j=1}^n \exp(\beta' \mathbf{X}_{ij})}.$$

Note from the above equation that those variables that do not vary over the technology alternatives (e.g., firm and industry-level covariates) simply cancel out. Hence, the conditional logit model is well suited for testing how the characteristics of the technologies influence entry choice and provides estimates that are robust to unobserved entrant or industry characteristics that are constant across the technology choices.

A key assumption underlying the conditional logit discrete choice model is that any pairwise comparison between choices is unaffected by the characteristics of alternatives other than the pair under consideration. This assumption is referred to as independence of irrelevant alternatives (IIA), and can be tested using Hausman and McFadden's (1984) test. We performed this test and found that our dataset exhibits IIA.

## RESULTS

Table 1 presents the descriptive statistics and correlations for the variables used in the regression analysis. Table 2 reports the results from the conditional logit models. Model 1 is the baseline model with control variables. Model 2 introduces the effect of technology performance to test Hypothesis 1, and Model 3 includes the effect of complementary assets to test Hypothesis 2. Testing of

Hypotheses 3 to 5 requires a comparison of the coefficients for the technology performance and complementary assets variables across the different types of entrants. Statistical inferences can be drawn by comparing the ratio of coefficients across the entrant groups or if coefficients are significant in one group but not in the other (Hoetker, 2005, 2006; Train, 1998). By separately modeling the technology choices for the different entrant groups, we also relax the somewhat problematic assumption that the unexplained variance is the same across the different types of entrants.<sup>9</sup> Models 4 and 5 estimate coefficients for diversifying and start-up entrants, respectively, and allow us to test Hypotheses 3. Models 6 and 7 estimate coefficients for diversifying entrants with related and unrelated pre-entry capabilities, and allow us to test Hypothesis 4. Finally, Hypothesis 5 is tested using Models 8 and 9 in which we separately estimate the coefficients for start-up entrants with related and unrelated founder experience.

The results from the baseline model suggest that the likelihood of entry into a technology increases with the number of firms and cumulative production. The effects of technical opportunity, annual production, and annual growth were insignificant. In Hypothesis 1, we predicted that an entrant is more likely to choose a technology with superior technical performance. The coefficient for technology performance is positive and significant ( $p < 0.01$ ) in both Models 2 and 3, providing support for this prediction. In Hypothesis 2, we predicted that an entrant is more likely to choose a technology for which the key complementary assets within the ecosystem are available than technologies for which they need to be developed. The significant positive coefficient ( $p < 0.01$ ) for complementary assets in Model 3 provides support for this hypothesis.

<sup>9</sup>The alternative approach for testing Hypotheses 4 and 5 entails interacting the type of entrants with the covariates for complementary assets and technology performance. However, this approach assumes that the unexplained variance is the same across the different groups of entrants. Violation of this assumption can lead to false inferences. Given that Hypothesis 3 can only be tested by comparing the ratio of coefficients for complementary assets and technology performance for diversifying and start-up entrants, respectively, we follow the more conservative approach for testing Hypotheses 4 and 5 by estimating a separate model for each type of entrant. As a test of robustness, we perform a supplemental analysis using interaction terms and find very similar effects for the different entrant groups.

Table 1. 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	0.26	0.44	0.00	1.00							
2 Technology performance	-1.07	0.47	-2.85	-0.60	-0.10						
3 Complementary assets	1.03	0.88	0.00	2.00	0.32	-0.34					
4 Firm count	22.25	24.77	0.00	102.00	0.30	-0.60	0.67				
5 Technical opportunity	1.09	0.07	1.00	1.33	-0.11	0.06	-0.27	-0.28			
6 Annual production	966.39	2727.77	0.00	30476.43	0.20	-0.34	0.34	0.73	-0.25		
7 Cumulative production (log)	2.35	1.25	-3.62	4.85	0.23	-0.37	0.74	0.74	-0.14	0.50	
8 Annual growth	0.84	0.77	-0.27	3.07	-0.18	0.17	-0.22	-0.11	-0.15	-0.05	-0.15

Number of observations = 653.

Correlations greater than 0.09 or smaller than -0.09 are significant at  $p < 0.05$ .

Models 4 and 5 report the estimates for diversifying and start-up entrants, respectively. The coefficients for technology performance and complementary assets are positive and significant for both start-ups and diversifying entrants. However, the magnitude and the level of significance of the technology performance coefficient are much greater for start-ups (1.601;  $p < 0.01$ ) than for diversifiers (0.613;  $p < 0.1$ ). In contrast, the magnitude and the level of significance of the complementary assets coefficient are much greater for diversifiers (1.167;  $p < 0.01$ ) than for start-ups (0.502;  $p < 0.1$ ). A comparison of the ratios of coefficients for complementary assets and technology performance across the two entrant

groups provides an understanding of the relative importance of these technological characteristics for diversifying and start-up entrants, respectively. The ratio is 1.90 for diversifying entrants and only 0.31 for start-up entrants. Hence, a diversifying entrant is willing to give up almost six times as much technology performance for the availability of the complementary assets than a start-up entrant would. Although statistical significance in the tests of differences between ratios of coefficients can be difficult to achieve (Hoetker, 2007), we find that the difference in the ratios is statistically significant ( $p < 0.05$ ). These findings offer strong support for Hypothesis 3 that, relative to technology performance, availability of complementary

Table 2. Conditional logit discrete choice model estimates of entrants' technology choice in the solar PV industry

	(1) All entrants	(2) All entrants	(3) All entrants	(4) Diversifying entrants	(5) Start-up entrants	(6) Diversifying (related)	(7) Diversifying (unrelated)	(8) Start-up (related)	(9) Start-up (unrelated)
Technology performance		1.095*** (0.265)	1.003*** (0.268)	0.613* (0.340)	1.601*** (0.468)	0.586 (0.498)	-0.197 (0.776)	1.803*** (0.693)	3.957*** (1.437)
Complementary assets			0.809*** (0.195)	1.167*** (0.305)	0.502* (0.281)	2.069*** (0.639)	0.387 (0.581)	0.772* (0.410)	0.722 (0.493)
Firm count	0.016** (0.007)	0.041*** (0.010)	0.034*** (0.010)	0.021 (0.013)	0.051*** (0.018)	0.018 (0.021)	0.059** (0.028)	0.042* (0.024)	0.019 (0.036)
Technical opportunity	-2.028 (1.726)	-1.208 (1.831)	-1.074 (1.889)	2.525 (3.074)	-3.278 (2.658)	2.400 (4.887)	3.768 (4.692)	-6.141 (5.411)	-3.000 (3.574)
Annual production	-0.000 (0.000)	-0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	-0.001* (0.000)	-0.000 (0.000)	0.002** (0.001)
Cumulative production	0.218* (0.122)	0.003 (0.131)	-0.418** (0.168)	-0.136 (0.282)	-0.652*** (0.229)	-0.374 (0.525)	-0.112 (0.453)	-0.410 (0.429)	-1.117*** (0.392)
Annual growth	-0.212 (0.182)	-0.429** (0.178)	-0.458** (0.186)	-0.127 (0.294)	-0.717*** (0.252)	-0.653 (0.652)	0.093 (0.437)	-0.250 (0.341)	-1.330*** (0.479)
Log-likelihood	-189.70	-180.42	-171.54	-88.59	-74.18	-39.07	-37.81	-37.05	-29.88
McFadden's pseudo- $R^2$	0.16	0.20	0.24	0.33	0.21	0.53	0.23	0.26	0.32
Observations	648	648	648	379	269	242	137	143	126
Entrants	171	171	171	98	73	63	35	37	36

Standard errors in parentheses, \* $p < 0.1$ ; \*\* $p < 0.05$ ; \*\*\* $p < 0.01$ .

assets has a significantly greater effect on the technology choice for diversifying entrants than for start-up entrants.

In Hypothesis 4, we predicted that, among diversifying entrants, the availability of complementary assets will have a greater effect for those entrants with related pre-entry capabilities than those with unrelated pre-entry capabilities. The estimates in Models 6 and 7 offer support for the hypothesis. The coefficient for complementary assets is only significant ( $p < 0.01$ ) for diversifying entrants with pre-entry capabilities that are related to the solar PV industry. These results suggest that the preference of diversifying entrants for entering with technologies for which the complementary assets are available is mostly attributable to diversifying firms with related pre-entry capabilities. These are the firms that can more readily leverage the available complementary assets to achieve faster commercialization, go down the learning curve, and potentially win the competition for technology dominance.

In Models 8 and 9, the coefficient for technology performance is positive and significant for start-ups with both related and unrelated founder experience. The coefficient for complementary assets is positive and very similar in magnitude

across the two types of start-ups. The ratio of coefficients for technology performance and complementary assets for start-ups with related founder experience is 0.43 and for those with unrelated founder experience is 0.18. Hence, as argued in Hypothesis 5, start-ups with unrelated founder experience seem to place greater emphasis on technology's performance superiority than start-ups with related founder experience. However, the difference between the ratio of coefficients was insignificant ( $p = 0.42$ ), indicating a lack of statistical support for Hypothesis 5.

**Robustness checks**

The solar PV industry witnessed a relatively long period of emergence, and entry into all four solar PV technologies was observed only after 1998. In order to ensure that our inferences are not subject to temporal bias, we estimated a model in which we only included the later wave of entrants. These results are reported in Table 3 and continue to support our predictions as our main results.

We performed a number of robustness checks that we report in Table S2 in the online Supporting Information. First, we tested for the effects of contact and deposition equipment separately rather

Table 3. Conditional logit discrete choice model estimates of entrants' technology choice in the solar PV industry for entry after 1998

	(10) All entrants	(11) Diversifying entrants	(12) Start-up entrants	(13) Diversifying (related)	(14) Diversifying (unrelated)	(15) Start-up (related)	(16) Start-up (unrelated)
Technology performance	0.946*** (0.282)	0.583 (0.354)	1.498*** (0.500)	0.613 (0.499)	-0.214 (0.861)	1.884** (0.758)	5.288*** (1.880)
Complementary assets	0.858*** (0.291)	1.289*** (0.405)	0.495 (0.480)	2.217** (0.943)	0.364 (0.596)	0.601 (0.557)	-0.013 (0.791)
Firm count	0.034*** (0.012)	0.023 (0.015)	0.054*** (0.020)	0.027 (0.030)	0.056* (0.030)	0.044* (0.025)	0.030 (0.047)
Technical opportunity	-0.918 (2.321)	2.181 (3.464)	-1.760 (3.504)	3.543 (5.138)	1.566 (5.611)	-5.623 (6.111)	3.594 (5.562)
Annual production	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	0.000 (0.000)	-0.001* (0.000)	-0.000 (0.000)	0.002** (0.001)
Cumulative production	-0.473 (0.319)	-0.241 (0.450)	-0.730 (0.520)	-0.678 (0.994)	0.004 (0.566)	-0.300 (0.671)	-0.854 (0.758)
Annual growth	-0.370* (0.206)	-0.022 (0.311)	-0.658** (0.290)	-0.512 (0.631)	0.159 (0.459)	-0.308 (0.372)	-1.830** (0.752)
Log-likelihood	-155.34	-81.51	-65.06	-37.15	-34.11	-35.45	-21.66
McFadden's pseudo-R <sup>2</sup>	0.24	0.34	0.20	0.53	0.26	0.25	0.38
Observations	592	356	236	228	128	136	100
Entrants	148	89	59	57	32	34	25

Standard errors in parentheses, \* $p < 0.1$ ; \*\* $p < 0.05$ ; \*\*\* $p < 0.01$ .

than as an aggregate measure (Models 17–19). Second, related pre-entry capabilities of diversifying entrants included upstream capabilities in manufacturing and downstream capabilities in marketing and distribution. Given that the upstream manufacturing capabilities may be more relevant for the manufacturing complementary assets that we consider in this study, we ran a separate analysis (Model 20) excluding diversifying firms with related downstream capabilities (i.e., 17 solar PV installers).<sup>10</sup> Third, for three of the four technology choices (a-Si, CdTe, CIGS), the solar PV module manufacturing process takes place in a production line that performs the fabrication of cells followed by their interconnection into modules. For c-Si technology, the production process for the cell is somewhat decoupled from that of the module. While a majority of entrants pursued the integrated manufacturing of cells and modules, 43 out of 103 entrants using c-Si technology pursued manufacturing of modules while procuring cells from suppliers of semiconductor materials. Hence, these solar PV module entrants did not require the deposition equipment. In our interviews, many industry participants suggested that integration is a desirable choice for entrants pursuing c-Si technology as it offers greater control over the key input and allows for maximizing the performance of the technology. This is evident from the fact that 19 of those 43 entrants also manufactured solar PV cells within a five-year period of their entry. As a robustness check, we ran an analysis excluding those c-Si entrants who did not manufacture c-Si cells (Models 21–23) as well as including these entrants but only considering the contact equipment as the key complementary asset for all entrants (Models 24–26). The estimates from all of these additional checks are qualitatively similar to our main results, giving us additional confidence in our findings.<sup>11</sup>

<sup>10</sup>Note also that all of the 17 solar PV installers that entered the solar PV module industry pursued technologies for which both the deposition and the contact equipment were commercially available. Hence, there does not seem to be a significant difference in the preference of diversifying entrants with upstream manufacturing or downstream distribution and marketing pre-entry capabilities. They both appear to place greater emphasis on the availability of complementary assets.

<sup>11</sup>Additionally, for Hypotheses 1 and 2, we also explored the use of mixed conditional logit models to bring entrant types into the regression and account for the potential unobserved preference of diversifying or start-up entrants for a specific type of technology. The results are robust to this alternative model. The reported

## DISCUSSION AND CONCLUSION

The emergence of a new industry is characterized by entrants pursuing distinct technological choices. These choices hold important implications for entrants' performance and the overall evolution of the industry. Strategy scholars have long considered the important role played by firms' complementary assets in shaping firm entry strategies and the resulting performance outcomes (e.g., Helfat and Lieberman, 2002; Mitchell, 1989; Teece, 1986). In this study, we broaden the locus of complementarities and consider both the redeployment of firms' complementary capabilities and the availability of complementary assets in the ecosystem to explain entrants' technology choices in an emerging industry. We argue and show that an understanding of the diversity of technology strategies pursued by entrants requires an explicit consideration of technology characteristics—core technical performance and the availability of complementary assets in the ecosystem, and how they interact with entrants' pre-entry experience and capabilities.

We test our arguments during the emergence of the global solar PV industry in which entrants pursued four distinct technological choices. We find that, on average, an entrant is more likely to choose a technology with superior technical performance and for which the key complementary assets are available. However, the relative importance of technical performance and availability of complementary assets towards entrants' technology choices depends on their pre-entry history. Diversifying entrants aiming to redeploy their pre-entry capabilities in new industries are more willing to trade off high technical performance for the availability of complementary assets. By contrast, start-ups, facing competition with diversifying entrants endowed with significant organizational capabilities, are more likely to trade off the availability of complementary assets for higher technical performance. Furthermore, the difference between diversifying and start-up entrants is primarily due to diversifying entrants with pre-entry capabilities that are related to the solar PV industry rather than those with capabilities that are unrelated. We also found some preliminary but inconclusive evidence that start-ups with founder

results are also robust to the exclusion of CdTe technology from the choice set, which witnessed the least number of entrants.

experience that is unrelated to the industry place greater emphasis on technical performance than start-ups with related founder experience.

While scholars have generated important insights linking firms' pre-entry capabilities and experience 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 (Adner and Kapoor, 2010). By showing that entrant's technology strategies are not only influenced by the technology's performance and the availability of complementary assets but also that this influence is asymmetric across diversifying and start-up entrants, we shed light on an important interaction between technology characteristics and firms' pre-entry history in a new industry.

Similarly, while scholars have explicitly considered that entrants choose different technologies during the emergence of an industry (e.g., Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Suarez and Utterback, 1995), limited attempts have been made to systematically explain these differences in entrant strategies. Existing explanations have focused on factors such as cognition (Kaplan and Tripsas, 2008) or bandwagon behavior (Abrahamson and Rosenkopf, 1993). By characterizing technologies according to the core technical performance and the availability of complementary assets as well as by considering differences in capabilities among diversifying and start-up entrants, this study offers a new explanation for entrants' technology choices in an emerging industry. Indeed, in our framework, start-up entrants appear to consider the capabilities of other entrants and the broader ecosystem in choosing a technology where they have a greater chance of successfully developing and defending an advantage. Similarly, diversifying entrants seem to identify interactions between their own capabilities and the complementary assets in the ecosystem that can be readily leveraged to commercialize a technology and obtain a defensible advantage.

The finding that the importance of complementary assets availability and technology performance towards entry choice varies according to whether diversifying entrants' pre-entry capabilities and start-ups' founder experience are related or unrelated to the industry illustrates the benefits of distinguishing between these types of pre-entry capabilities and experience. While the empirical

literature has often focused on start-ups vs. diversifying entrants, our results reinforce the value of considering a finer categorization of entrants' pre-entry characteristics than whether they are established or new firms (Helfat and Lieberman, 2002).

In more practical terms, we offer a parsimonious framework for managers and entrepreneurs to evaluate their firm's technology choice in a new industry. Early in the industry's life cycle, when different technologies compete for dominance, there is high uncertainty about which technology will "win." If a technology has high performance and key complementary assets are available in the ecosystem, it presents an attractive entry proposition (i.e., low barriers to entry and likely to win the technology competition). Under these circumstances, greater competition within a superior technology could benefit those entrants with a greater stock of pre-entry capabilities that are related to the industry. If a technology has low performance and complementary assets need to be developed, it is the least attractive alternative. However, in many cases, firms face a trade-off between technology performance and complementary assets availability. If a technology has high performance but complementary assets are not readily available, firms have to allocate additional resources to develop complementary assets but also have the opportunity to develop specialized complementary capabilities with a superior technology. In contrast, if a technology has somewhat lower performance but complementary assets are available, firms face lower commercialization challenges but are subjected to a potential lock-in into an inferior technology. Given this trade-off, diversifying entrants with related capabilities may benefit more by choosing the latter technology where they can quickly utilize their pre-entry capabilities to capture first mover advantages, whereas start-ups lacking such capabilities may benefit more by choosing the former technology where they can develop unique capabilities with a superior technology. The eventual performance outcomes for the diversifying entrants and start-ups will, of course, depend on the evolution of the performance profiles of the competing technologies and the extent of challenges associated with the development of complementary assets.

The study has a number of limitations. 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 examine an important and emerging industry, the variation in complementary assets across the different technologies is confined to the manufacturing equipment. Clearly, the spectrum of complementary technologies 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 upstream and downstream complementary assets (e.g., Adner and Kapoor, 2010). Third, our measure of complementary assets availability is based on the years in which the deposition and contact equipment were commercially available. The measure is not sensitive to the price-adjusted quality of the equipment. Finally, while our database captures all major global firms and more than 95 percent of global production capacity, we do not have information on smaller local players.

Despite these and other limitations, we hope that the study has provided an important step forward in our understanding of the process of entry in an emerging industry. Evidence from the solar PV module industry sheds light on the difficult trade-offs that entrants face between technology performance and availability of complementary assets in the ecosystem. We show how understanding the variance in entrants' technology strategies requires an explicit consideration of how these trade-offs interact with their pre-entry history so as to offer them a path towards sustainable competitive advantage.

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## SUPPORTING INFORMATION

**Additional supporting information may be found in the online version of this article:**

Table S1. Classification of entrants with related and unrelated pre-entry capabilities and founder experience

Table S2. Robustness checks - conditional logit estimates of entrants' technology choice in the solar PV industry