Too Little, Too Early: California's Transient Advantage in the Photovoltaic Solar Industry

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Abstract: Throughout its brief history, California has established itself as a national or international leader in key industries — such as aerospace, computing and entertainment — through early mover pre-emption and strong clustering effects. California firms were the initial world leaders in producing photovoltaic (PV) solar cells and dominated the initial aerospace niche market. However, these early efforts failed to create a durable cluster, and when the U.S. market lost interest in renewable energy during the 1990s, California firms were largely surpassed by Japanese, German and Chinese producers that focused on the mass market of using PV to displace fossil fuels for electricity generation.

The paper reviews the history of the California PV producers in three phases: aerospace niche markets of the 1950s and 1960s, a brief policy-induced effort at electricity generation in the 1980s, and a 21st century resurgence fueled by Silicon Valley venture capital. It then discusses why the early entry of the California firms failed to translate to sustained advantage for the firms or the region.

Keywords: industry clusters, pioneer advantage, renewable energy, industry emergence

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Because of California's sunny and mild subtropical climate, it is not surprising that it was an early leader among the United States in developing and harnessing solar energy. The state also drew upon its central role in the early US space program, its semiconductor manufacturing infrastructure and more than 30 years of state policies promoting the use of renewable energy.

However, early efforts during the 1960s and 1980s to build the state's solar industry proved premature, as technical improvements and buyer adoption failed to match wildly optimistic predictions of abundant free electricity that would transform society and generate riches for solar manufacturers. While various solar technologies predate the cellular phone (1979), personal computer (1975) and even the integrated circuit (1961), for decades the solar industry has remained a small fraction of the size of each of these later industries. When solar power finally became a billion dollar industry in the 21st century, most of California's 20th century pioneers had exited while newer firms struggled to gain share in a commoditized global industry.

This paper begins with a brief review of locational factors for competitive advantage, and then examines three phases of the evolution of California's postwar solar industry: aerospace niches, temporary responses to the oil crises, and then its late entry into a broader global industry spawned by concerns about global warming. It then discusses why the early entry of the California firms failed to translate to sustained advantage for the firms or the region.

1. A Review of Clustering Mechanisms

For firms creating technological innovations, a particularly important locational factor is the availability of knowledge spillovers from rivals and university research (Simard and West, 2006). Of particular importance in the growth of new industries in a given region is the knowledge carried through intra-firm mobility of skilled workers — whether in computers or winemaking (Saxenian, 1994; Giuliani, 2007). In this regard, California has unusually high degrees of labor mobility, fueled in part by an unusual legal policy that bars enforcement of most non-compete agreements (Gilson, 1999; Fallick et al, 2006). At the same time, firms competing in globally traded industries must selectively combine both local tacit knowledge with globally dispersed best practice (Asheim and Isaksen, 2002)

Industry-specific economic development has emphasized the geographic interdependence of Marshallian industrial district. For example, dense local networks of suppliers enabled firms to create complex products without complete vertical integration; the existence of such integrators creates demand for prospective supplier firms, creating a ready market for the creation and growth of small specialized suppliers (Scott and Mattingly, 1989). Meanwhile, geographic co-location also enables the production of complementary goods and services, such as the software industry that arose in Silicon Valley to supply software for personal computers such as the Apple II (Rogers & Larsen, 1984). While California had among the largest land area and (after 1965) the greatest population of any of the states, its efforts to establish world-class industries in the 20th century were arguably successful in only three cases: motion pictures and related entertainment industries (Scott, 1999), aerospace (Scott and Mattingly, 1989) and information technologies (Rogers & Larsen, 1984; Bahrami and Evans, 1995). The presence of the latter two industries would later prove important in developing California's solar industry.

California's climate was certainly an advantage for harnessing solar energy, which does best at low latitudes and limited cloud cover. The best US region for solar energy is the desert Southwest (Roberts, 2008). California enjoys both strong insolation in key population centers — important for distributed residential and commercial solar energy installations — and in one of the best regions in the world for utility-scale solar generation, the Mojave Desert located less than 100 miles from Los Angeles, the country's second largest population center. In addition to weather, the state also had leading technological universities, an entrepreneurial infrastructure and (after 1974) that nation's most aggressive polices in support of renewable energy. California would thus appear to be a natural home for both the use and production of solar technologies.

However, unlike the aerospace, entertainment or computer industries, the larger market segments for the solar energy industry began life competing in commodity industries, without opportunity for differentiation. An added complication came from the unpredictable prices for proven energy competitors — particularly in the decades following the 1970s energy shortages and price spikes that attracted unprecedented interest from entrepreneurs, energy buyers and policymakers. Solar energy was also less reliable than these existing substitutes.

During the past century, solar technologies fell into three major categories. The simplest of the technologies was using solar energy to heat water, typically for residential use; this relatively low-tech approach provided hot water for Southern California residences from 1895-1925, and then again after the oil crises of the 1970s. The next simplest used solar energy to boil water (or another liquid) and drive a steam turbine to generate electricity in large "solar farms"; these solar thermal facilities were California (and at one point, the world's) main source of solar-generated grid-connected electricity during the 1990s, with a renewed burst of interest from 2008-2010. [1]

Here I focus on the eventual mass market for solar energy, the direct generation of electricity via photovoltaic (PV) panels made from semiconductor materials. I consider three major historical periods for California's PV industry: the space program (1955-1970), the energy crises and their aftermath (1974-1990), and finally concern with global warming (2000-present).

2. Aerospace Niche Markets

Although the silicon photocell was invented at Bell Labs in New Jersey, Southern California firms (Table 1) quickly became the world leaders of photovoltaic technology, commercializing

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[1] A summary of solar hot water and solar thermal power in California from 1900-2010 can be found in West (2011).

this (still) expensive technology for aerospace niche markets in the 1950s and 1960s.

2.1 Invention of the Photovoltaic Cell

The photoelectric effect was noted back in 1839, but it wasn't until 1954 that three Bell Labs researchers — Daryl Chapin, Calvin Fuller and Gerard Parson — invented the first practical photoelectric cell, using the silicon material that had been the basis of the transistor seven years earlier (Engel, 1954; Perlin, 2004). The solar cell attracted widespread publicity and fanciful predictions of societal transformation, but only limited application during the first decades.

AT&T used the cells for its own products when in 1962 it launched the Telstar satellite to relay TV signals across the US (Bailey et al, 2002). However, initial commercialization of the solar cell came through licensees: in 1955, Western Electric began licensing the solar cell patent, apparently part of AT&T's broader policy of licensing its technology to other domestic firms (cf. Moll, 1993). Solar cells remained a small niche of the semiconductor industry in the 1950s and 1960s, as the bulk of the commercial investment focused on the broader market of replacing vacuum tubes with semiconductors. Aerospace applications for semiconductors provided the critical early demand that fueled the growth of the industry throughout the 1960s (Leslie, 2000).

2.2 Space Satellites

The first licensee of the Bell Labs "solar battery" was National Fabricated Products of Chicago, which began production in 1955 (Time, 1955). Although a *Life* (1955) photo shows the NFP "battery" as being promoted as providing "free solar power" for "100 years," the "free" power came at a high price that eliminated all but novelty markets: a single 4'x4' NFP panel in the *Life* photo contained 400 cells would have cost $10,000 (worth more than $80,000 in 2010). Cells were expensive to make due to the cost of purified silicon, and large number of cells were needed due to a low conversion rate of only 6% (Time, 1955). NFP was purchased in 1955 by

Hoffman Electronics of Los Angeles.[2] A 1958 *Popular Mechanics* article focused on Hoffman's hoped-for markets, including examples of a solar-charged flashlight, solar-charged radio, a solar-powered clock and toys, as well as sketches of a solar-powered home (Stimson 1958).

For more than decade, the lead market for solar cells was not toys but unmanned space probes and satellites that needed power for months or years, far longer than the life of chemical batteries.[3] As with digital communications studied by West (2008), Hoffman and others targeted the space market because it was a small volume, price-insensitive market without satisfactory substitutes. As with communications, the solar supply industry for unmanned space exploration was concentrated around the Jet Propulsion Laboratory (JPL) in suburban Los Angeles.

The first use of solar cells in space came in March 1958, when Vanguard I was America's 2nd successful satellite launch and the 4th manmade object in space. Its one-watt solar cells lasted six years, versus four months for the chemical batteries used in the Explorer 1 satellite launched two months earlier. NASA itself helped launch the solar industry's first professional society, the IEEE Photovoltaic Specialists Conference, by hosting the conference at its headquarters and research labs from 1961 to 1968.

According to a NASA memoir, Hoffman was the lead supplier of solar cells to the early US space program, having supplied to "80 to 85 percent" of NASA's solar cell needs as of March 1960 (Glennan 1993: 96). This continued with the JPL-designed Ranger series of lunar probes (1961-1965). For example, Ranger 4, the first US spacecraft to reach the moon, had 20 square feet of Hoffman solar panels comprising 8,680 solar cells that produced 175-205 watts of power (NASA, 1962). Hoffman was also listed as a leading solar supplier (along with International Rectifier and GE) in a 1963 study of power sources for fallout shelters: based on component list

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[2] Company president H. Leslie Hoffman moved to Los Angeles in 1929, and in 1941 "took over a bankrupt Los Angeles radio manufacturing company" (Hoffman, 1957: vi).

[3] The manned Gemini and Apollo missions lasted less than two weeks and were powered by fuel cells.

prices, a 10 kW system was estimated to cost $1.5 million (Lauck & Overbye, 1963).[4] Founded in 1947, International Rectifier began making solar cells in 1958; in 1960, it supplied them for the first weather satellite (TIROS I) and demonstrated a solar-powered 1912 Baker electric car.

A key Hoffman rival was Spectrolab, a solar-only startup founded in 1956 by Alfred Mann. When purchased by Textron in 1960 for $300,000, Spectrolab bragged that it "produced most of the solar energy converters supplying power to U.S. satellites now in orbit" (*Los Angeles Times,* 1960). Mann also started a second company, Heliotek, acquired by Textron at the same time; he continued to run the two companies until 1972. Among other missions, Spectrolab provided solar cells to Pioneer 1 (1958), Explorer 6 (1959) and Apollo 11 (1969) ("Our history," 2011). The company was later sold to two defense contractors: first Hughes Aircraft, and then Boeing.

These firms competed for business and technical talent. For example, a survey of PV trends by Martin Wolf was presented at the 1961 Winter Convention on Military Electronics while at Hoffman, but published in *Solar Cells* as a Heliotek employee (Wolf, 1961). In 1985, Hoffman and Spectrolab controlled about 95% of the US civilian and military space market, making high efficiency, high-cost cells optimized for the harsh conditions of space (Goldstein, 1985).

3. Energy Crises

3.1 Bringing PV Down to Earth

The 1973 and 1979 oil crises created interest in California and the U.S. for solar energy as a way to power homes and businesses. However, while the existing space-oriented solar industry in Los Angeles brought nearly two decades of PV experience — and had also sold to terrestrial niche markets such as remote navigational buoys and radio beacons — it faced wrenching changes in adapting to high-volume markets replacing conventional electricity. As Shrum (1985:

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[4] Such a calculation would not include mounting, installation or DC/AC conversion, which today account for about half the price of a completed solar system. Still, recently such a system (fully installed) would cost about $80,000 (Pinkham, 2009), about a 20-fold improvement in 50 years.

65) concluded

> [A]lthough the current technological program is an outgrowth of the space program … the cells which existed in the early 1970s were by and large expensive, high-performance devices. A product for the terrestrial market would have quite different characteristics, including weather resistance, but with cost as the dominant constraint.

In response to the crisis, the existing PV space industry — created with federal procurement dollars — moved quickly to call for increased Federal funding for terrestrial applications, which was supported by local Republicans (*Los Angeles Times,* 1973). As a consequence, the Federal government launched a major R&D project to tap that space-oriented photovoltaic experience and adapt it for larger, more cost-sensitive terrestrial markets. From 1975-1986, the Energy Research and Development Administration (and later the Department of Energy) spend $235 million to fund the Low-Cost Silicon Solar Array (LSSA) project, an umbrella research program for university and industry research.[5] It was administered by JPL, the Federal-funded research & development laboratory with the longest experience in space applications of PV and strongest ties to the Los Angeles aerospace industry. By the late 1970s JPL's leadership in solar R&D was eclipsed by the Energy Department's new Solar Energy Research Institute in Colorado.

Hoffman (now Applied Solar Energy Corp. or ASEC) continued to emphasize military and NASA satellites throughout the 1980s, and did not diversify into civilian satellites until the end of the Cold War cut defense budgets (Vartabedian, 1993). Like ASEC, Spectrolab continued to supply expensive, high-efficiency cells to the military and civilian satellite market.

In fact, the greatest contribution made by either firm to the mass market came with a Spectrolab spin-off. In 1975, Spectrolab president Bill Yerkes quit in 1975 to start Solar Technology International with $80,000 in personal savings. Lacking capital to expand, he sold

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[5] In contrast to JPL's $21 million average annual allotment, NSF funding for *all* US solar research in FY1974 totaled $12 million (*Los Angeles Times,* 1973). However, total Energy Dept. funding for photovoltaic research and other expenditures reached $159m in FY1980 (Roessner, 1982).

the company to Los Angeles-based Atlantic Richfield (Arco) in 1977 (Quinn, 1985). The resulting Arco Solar leveraged Arco's oil wealth to rapidly scale up manufacturing, temporarily becoming the world's largest PV supplier and California's dominant PV supplier of the 1980s.

Of the 11 leading US solar makers in 1978, three focused on the terrestrial markets — Arco Solar, Solarex, Solar Power — and five were based in California: Arco Solar, ASEC, Silicon Material, Solec and Spectrolab. Instead, during the 1970s revenues from product sales were eclipsed by Federal R&D funding, diminishing the value of the California location. Overall, the PV market remained small, with total 1978 US production about 0.8-1.0 megawatts; in 1980, U.S. sales totaled $39 million with global sales less than $50 million (Roessner, 1982).

3.2 Desert Solar Farms

In the 1980s, California's Mojave Desert was the site of key experiments that pioneered the creation of utility-scale solar power generation, taking advantage of new Federal and state government policies to encourage electricity generation from renewable sources for sale to electric utilities. The first efforts used solar thermal power to heat liquid and drive turbines. Southern California Edison and other utilities funded two 10 megawatt demonstration projects near Barstow: Solar One (1980-1988) and Solar Two (1995-1999). Then from 1984-1990, Luz International built nine generating plants at three Mojave sites totaling 354 MW that accounted for more than 95% of the world's grid-connected solar power (Lotker, 1991; West, 2011).

Also during the 1980s, four megawatt-scale photovoltaic systems were installed in the California — at that point, the largest in the United States and in the world. In fact, each of these megawatt-sized plants totaled more than all of Europe combined (Hubbard 1989). All used solar panels from Arco Solar. Although strongest in the California market, overall Arco Solar had 16 of the 35 small and large first decade US PV systems surveyed by Durand and Bowling (1993).

Two of these utility-scale PV systems were owned and operated by Arco Solar. The world's first megawatt-sized PV plant began service in 1983 in the Mojave near Hesperia, adjacent to SCE's Lugo power substation. The same year, Arco began generating power for PG&E at its Carrisa (Carrizo) Plains facility, located between Bakersfield and San Luis Obispo in Central California; by 1985, the system totaled 6.5 MW,[6] and Arco announced plans to expand it to 16.5 MW (Siimberger and Leonard, 1984; Summer et al, 1988). However, due to poor design and inadequate testing, the solar cells degraded when exposed to UV light; performance of the Carissa Plains facility fell 70% in only seven years (French et al, 2011). In January 1990, Arco sold both plants to private investors who dismantled them for parts over the next two years.

Better results were obtained by the Sacramento Municipal Utility District, which built two 1.2 MW solar farms adjacent to its Rancho Seco nuclear power plant, the first using Arco panels and the second using primarily Arco panels. After closing the nuclear power plant in 1989, SMUD added four more solar fields at Rancho Seco, totaling 3.2 MW by 2004.

The persistence of SMUD notwithstanding, experiments in grid-connected solar generation were an economic failure as oil and natural gas prices declined dramatically after 1982, while PV prices failed to fall as quickly as predicted. Meanwhile, the capital costs for a PV system in 1997 were still three times that of an equivalent solar thermal plant (Trieb et al, 1997).

4. Global Warming and Global Competition

Luz and Arco Solar created the largest grid-connected solar facilities in the world, and the firms were the largest US suppliers of solar technology of the 20th century. But declining fossil fuel prices brought a virtual end to US consumer, commercial and utility interest — and government subsidies— for using expensive PV cells to replace traditional sources of energy. As

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[6] PV facilities are customarily measured by their peak total panel (DC) power output, even though 10-20% of that power is lost in the conversion (via an inverter) to AC.

a result, California firms remained focused on their niche markets, lagging those of other countries with interventionist policies and greater public concern about global warming.

4.1 Global Competition

As solar faded from public interest in the US during the 1990s, efforts to develop PV as a substitute for conventional energy shifted to countries that had higher energy prices, higher environmental awareness and more active government policy, particularly Japan and Germany. As a result of such offshore growth, the production of grid-connected solar cells finally passed off-grid uses (such as calculators and satellites) for the first time in 2001 (Morton, 2006).

Large Japanese corporations diversified into solar through internal ventures, supported by the cash flow from their existing business. Leading PV manufacturers included Kyocera (a semiconductor materials company), Mitsubishi Electric (a power equipment company), Sanyo (a consumer electronics company) and Sharp (a leading manufacturer of LCD screens).

Meanwhile, Germany developed the most aggressive support for the purchase of renewable energy of any government in the world. In 1991, it created a unique policy innovation, the feed-in-tariff, which guaranteed a specified long-term price for electricity from renewable sources. As with California solar farms of the 1980s, the prospect of a known market for energy output allowed borrowing to buy and install solar equipment. However, unlike in California, Germany's 1991 (and 2000) law guaranteed the price for 20 years, at a price above market prices (subsidized by energy users). This virtually eliminated the investment risk for financing purchases and led to an explosion in the German wind and PV markets (Wüstenhagen & Bilharz, 2006).

By the late 1990s, the US was no longer the lead market in the global PV industry, which is split almost equally between the US, Japan and Europe. In 1998, the US was responsible for only 54 MW of the 152 MW of global solar production (National Research Council, 2000).

Of that US output, some of it was no longer owned by US firms, particularly as major oil companies gave up on solar. In 1990, Arco sold Arco Solar's PV manufacturing to Siemens of Germany to create Siemens Solar, which in turn was acquired in 2002 by Royal Dutch Shell to become Shell Solar. In 2006, Shell Solar was acquired by SolarWorld AG, a German solar manufacturer formed in 1998 to take advantage of the expanding German PV market.

During the 1990s, a lack of capital and domestic markets stalled Silicon Valley's first major PV company: SunPower. SunPower had been launched in 1985 in the Bay Area by Stanford professor Robert Swanson, who left Stanford in 1991 to become its full-time CEO. SunPower successfully developed a high-efficiency terrestrial solar cell for niche markets, and worked with ASEC (née Hoffman), Spectrolab and Solarex on a Federally-sponsored concentrating PV research project that was cancelled in 1992 (Swanson, 2000). With the dearth of Federal funding and limited capital availability, its growth stalled at less than $10 million in annual revenues. However, Cypress Semiconductor acquired the company through investment of $143 million from 2000-2004, and that capital for the first time allowed SunPower to ramp up manufacturing to address mass markets. Cypress later spun SunPower out via an IPO and stock divestiture that brought its shareholders a net gain of $3 billion (Colatat et al, 2009; Rodgers, 2010).

4.2 Silicon Valley Responds to Renewed Interest

After 2000, increased environmental concerns brought a flood of new US venture capital investment into "clean" technologies, which reached $1.6 billion in 2005 (Morton, 2006). Among these investments were dozens of PV startup companies — most located in Silicon Valley to have access to VC. The entry of new firms in Silicon Valley was also aided by redeployment (the "flexible recycling" of Bahrami and Evans, 1995) of machine tools producers and materials engineers that had previously supported the local semiconductor manufacturing industry before that industry moved to lower-cost regions. By the end of the decade, the availability of universities, suppliers and customers in the Bay Area created strong clustering effects as the state's center of solar cell production shifted to the region (Böttcher 2009).

The increased environmental concerns (and prospect of job and investment growth) also brought renewed financial support from the state and national governments. In early 2006, California announced the California Solar Initiative, which would increase electricity bills by $2.8 billion to pay purchase subsidies for residential and commercial solar panels (Taylor et al, 2007). And in 2009, the new Obama Administration won passage of a $787 billion American Recovery and Reinvestment Act that included $92 billion in spending for clean technologies, including $32.8 billion for renewable energy (SustainableBusiness.com, 2009).

Most of the new US firms used thin-film photovoltaic designs that deposited a thin film of silicon or other semiconductor material on a glass substrate. The technology had been discovered in the 1960s, and for decades researchers had predicted that such systems could deliver an order of magnitude improvement in module cost (e.g. Barnett and Rothwarf, 1980). However, the sizable technical problems had never been solved. The prospect of a new technology that would provide competitive advantage for a potentially lucrative market attracted a range of new entrants. A total of 46 U.S. firms entered the market from 2004-2008, attracting $1.8 billion in venture capital and expanding production fifty-fold in six years (Mehta, 2010).

The most successful of the thin film companies began much earlier. Glasstech Solar was founded in 1984 in Ohio by tempered glass expert Harold McMaster (Welles, 1998). In 1999, the company was acquired by investors, renamed to First Solar and later moved to Arizona. The company had its IPO in 2003. In 2009, First Solar became the first firm in the world to ship 1 gigawatt of capacity, but in 2011 its production slipped to second after China's Suntech.

Although based in Arizona, it had a thin film research facility in Silicon Valley and by 2010 had plans to use its PV technology to build California solar farms totaling more than 1 gigawatt of capacity, in the Mojave Desert and on the Carissa Plains.

However, the best known thin film company was Silicon Valley's Solyndra, founded in 2005 by Christian Gronet who held a Stanford PhD and worked for a decade at Applied Materials, the leading US supplier of semiconductor manufacturing equipment. Solyndra quickly grew to be the 2nd largest US thin film manufacturer, but then cancelled its announced 2009 IPO due to deteriorating financial performance. Pressured by declining world prices for silicon solar panels, Solyndra filed for bankruptcy in August 2011, defaulting on $1.1 billion in private equity capital and a $535 million Federal loan guarantee, with the later default triggering a national scandal.

Solyndra was not the only victim of declining prices and increased global competition triggered by the entry of high-volume, low-cost Chinese manufacturers who in 2009 passed their German counterparts to be the largest in the world. Other Silicon Valley thin film companies raised hundreds of millions in venture capital but were neither able to grow their way to financial self-sufficiency nor execute an IPO. Instead, a more successful area of innovation for US firms came in the stage of the industry value chain that was not globally traded, specifically installation financing. Silicon Valley startups such as SolarCity and Clean Power Finance create a model of solar leasing that simplified consumer installation of rooftop solar PV panels into a more familiar pattern: instead of paying a large up front sum to buy panels, homeowners paid a monthly rate that was often the same or less than their existing monthly electricity bill.

California firms also continued to pioneer utility-scale solar farms. In 2010 alone, California regulators approved eight solar thermal plants totaling 2,770 megawatts (West, 2011). However, rapidly declining PV prices due to global competition prompted the industry to shift planned developments from solar thermal plants to instead use PV (Kanellos and Prior, 2010).

5. Discussion

The use of solar energy to replace fossil fuels has held great promise for more than a century, and for nearly 60 years, California entrepreneurs have sought to leverage that promise to create successful firms. These entrepreneurs — as well as investors, policymakers and even the general public — assumed that solar energy would bring the same sort of success as did the state's other technology-based industries. But early California firms failed to achieve sustained competitive advantage due to premature entry, volatile demand, inability to create sustained technological advantage and large-scale entry by foreign competitors in a commoditized global market.

Here I review some of the factors behind California's transient advantage in PV, and the implications both for competition in new industry and the birth and growth of industry clusters.

5.1 Early Entry and Early Death

During the initial phase of the PV industry in the 1950s, California firms jumped to an early lead in finding markets, focusing on customers where other sources of electricity were unavailable, notably outer space. While two firms succeeded in their niche markets for decades, they were not ready for the long-imagined mass market: competing on price with fossil fuels and other established sources for providing electricity to grid-connected homes and businesses. That eventual mass market lay dormant, awaiting sizable government purchase subsidies as well as nearly 100-fold price reductions through experience curve scale economies and learning effects. By 2010, global PV output totaled about 17 billion watts of PV cells worth $70-80 billion.

Efforts to use PV to compete with grid-connected electricity were marked by three phases (Table 2): US energy crises (1975-1986), interest in Japan and Germany (1990-2000), and global competition to develop and sell renewable energy equipment (2000-present). Across all four (particularly the earliest) phases, California firms faced a common set of problems.

Inconsistent Public and Policy Support. State (and national) policy support — and the underlying public sentiment — swung wildly during the period 1960-2010. High levels of interest and subsidies in the 1970s and 1980s were replaced by indifference of the 1990s when the real price for fossil fuels fell from 1980 to 1999 — a trend reversed only after 2000. Even though Federal R&D spending on solar (and PV specifically) was higher under Democratic than Republican administrations, spending fluctuated dramatically within each administration (Figure 1). The lead that California firms held in 1965 (or 1985) was by 2000 lost to Japanese, German and later Chinese competitors supported by longer-term policies.

Failure of Technological Differentiation. As with countless Silicon Valley firms before and since, California PV firms sought competitive advantage through technological innovation, but the PV firms failed in those efforts. Solar energy produces an undifferentiated electron, and performance improvement is limited by the laws of physics to a single order of magnitude, from the original 5% efficiency to perhaps 50%. Thus, competition is based on gradual cost reduction, but — as Solyndra discovered — the rate of cost reduction through thin film technological innovation failed to keep up with improving efficiencies in the mature, standardized silicon technology used by the rest of the world's photovoltaic manufacturers.

Unexpectedly slow industry growth. Optimistic 20th century predictions of a bright future for solar energy failed to materialize. The technology improved more slowly than predicted, with cost-efficiency doubling every decade (versus every two years for semiconductors), while the price of substitutes fell rather than rose. Hoffman Electronics made solar cells in 1955 but home solar panels were not a mass market consumer product until after 2000; in contrast, consumers began buying personal computers in 1975, 16 years after Fairchild Semiconductor was founded.

Lack of Intermediate Niche Markets. The markets for PV cells in the 1960s and 1970s were in small price-insensitive niche markets like space satellites and remote communications beacons. Starting in the 1980s, California PV makers sought to directly compete in the billion-dollar commodity energy markets. Unlike other technologies such as semiconductors and digital communications (cf. Leslie, 2000; West, 2008), 20th century PV producers failed to find an intermediate-sized market to help scale up from the small niche to mass consumer markets.

Need for Patient Capital. Producing and selling solar systems was very capital intensive. The lack of intermediate markets meant that firms could not grow their assets gradually based on retained earnings, as did California's leading semiconductor products, Intel and Qualcomm. US firms were unable to access significant VC until after 2000; even so, as Hargadon and Kenney (2012) argue, the relatively slow growth and increasing capital requirements needed by renewable energy firms are beyond the limits of VC investors. In the 1990s, German producers gained the world's leading scale economies through guaranteed renewable energy purchase contracts mandated by the national government. The only PV producers that have obtained the capital necessary to achieve today's necessary scale economies are Chinese firms, which received more than $30 billion in government financing from 2008-2010 (Osborne, 2011).

5.2 Cluster Formation

Unlike the 21st century Silicon Valley cluster fueled by the availability of local venture capital and semiconductor technology, the mid-20th century cluster of PV makers arose from individual actions of Los Angeles-area entrepreneurs (following the model of Francis et al, 2005). The earlier cluster included labor mobility and at least one spinoff, but during the 1960s and 1970s its health was limited by the small size of the US and global market for PV cells.

Clusters need an ongoing source of upgrading to remain competitive, particularly in terms of knowledge and capabilities (Porter, 1998). Unlike more familiar examples of tech transfer in clusters, universities played little role in the L.A. cluster, with the research mainly performed and funded by the government and private industry. For example, in Roessner's (1982) list of 293 US solar patents among those granted from 1969-1978, about one quarter were each assigned to government, solar firms and aerospace companies (particularly satellite makers); only six patents were held by a university (MIT). Due to the small market size, PV makers had a small role funding the industry's research, but were well represented in government R&D grants; as with most Federal spending decisions, those grants were spread around the country, thus diluting clustering effects. Overall, the firms' limited manufacturing volume and R&D in the 1970s — as well as declining U.S. interest in the 1990s — prevented these firms from gaining experience curve effects needed to compete in the global market that eventually emerged in the 21st century.

The one hope for the cluster's breakthrough came in the 1980s from Arco Solar. Using the capital of parent company Arco — Southern California's largest oil company — it took advantage of the state's solar resource and a favorable regulatory climate to create the first megawatt-scale PV solar farms, accurately anticipating the approach (and even the locations) to be used by solar farms 25 years later. If it had succeeded, it would have created a demand for solar cells in the American southwest that would have sustained the company for years, attracted entry by other US firms and developed capabilities and scale that could have been used for exporting large volumes of solar panels to other parts of the world (as German and Chinese solar manufacturers did in the 21st century). Instead, the capital costs were too expensive to compete with traditional electricity sources, while reliability problems undercut Arco Solar's ability to attempt follow-on projects at other locations. When plans to build PV solar farms in the Southwestern U.S. finally resumed beginning in 2010, developers sourced solar panels from

Silicon Valley's SunPower, Arizona's First Solar and low-cost foreign producers.

If not for the rise of renewable energy in the 21st century, the L.A. solar makers might have been considered a successful cluster serving a small niche market — an example of Asheim and Isaksen's (2002) regionalized national innovation system, in which the knowledge was linked to a national or global market rather than intra-regional knowledge flows. However, by focusing on its niche, the firms did not develop the strong rivalry (identified by Porter 1998) necessary to compete in the eventual global market, and instead remained small specialists who watched the emergence of a mass market a thousand times larger than their niche.

Finally, other than a few customers — JPL and the L.A. aerospace companies — the early cluster lacked any leadership or direction. With the exception of JPL's decade of terrestrial research, these customers remained focused on space applications with little interest helping the local firms diversify. Meanwhile, after the urgency of renewable energy development faded at the state and national level in the 1980s, there was no government interest in helping grow the local firms through intermediate-sized markets to be ready for the eventual mass market.

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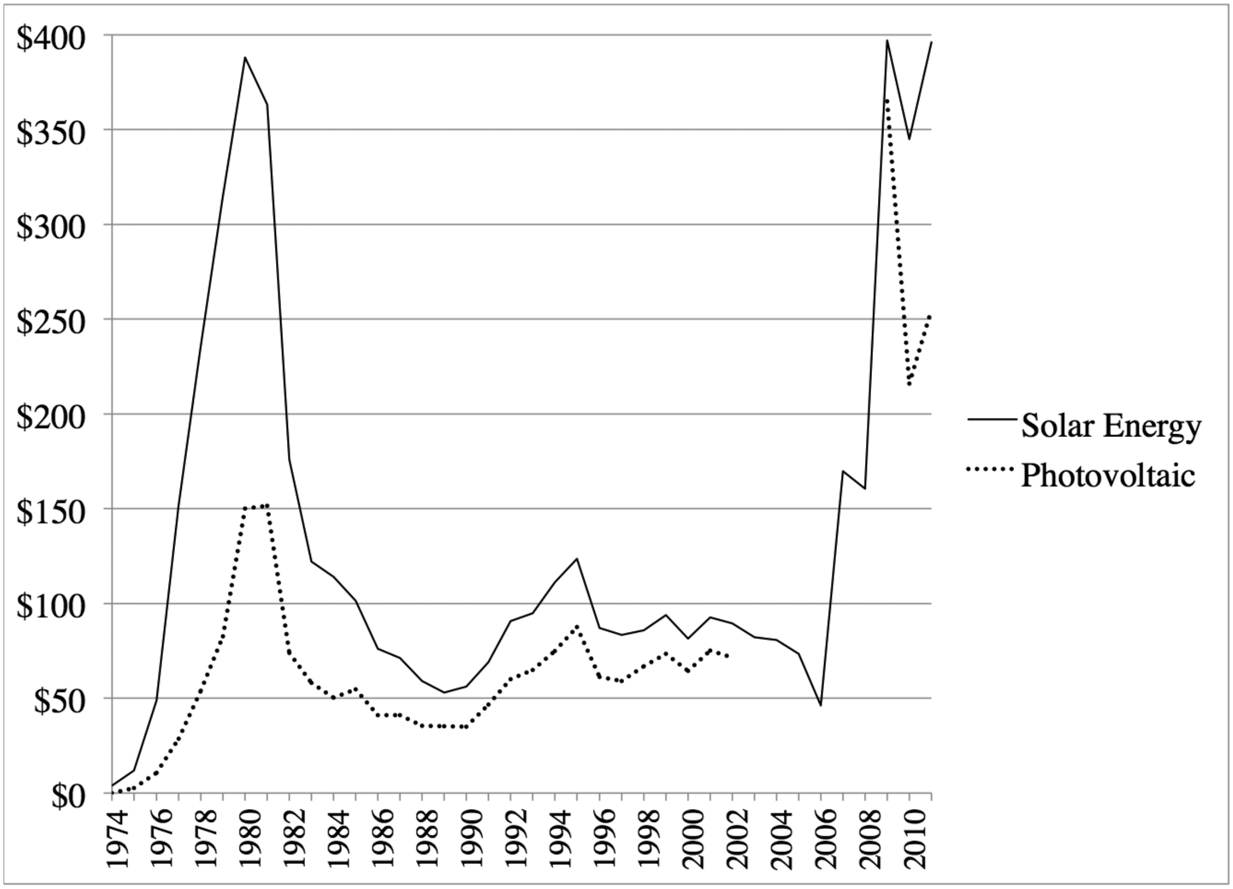
7. Tables and Figures

Firm	**Market and Technology**	**Born (entered)**	**Reason in California**	**Exit**
Hoffman Electronics	Aerospace and specialty PV	(1955)	Founder's previous employer	Acquired by Centralab (ca. 1968), Optical Coating Laboratories, Inc. (ca. 1975); renamed Tecstar (1996); bought by Emcore (2002)
International Rectifier	Aerospace and specialty PV	(1958)	Founder's previous employer	IPO in 1960; abandons solar in 1970s
Spectrolab	Aerospace PV	1956	Military	Acquired by Textron (1960), Hughes (1975) and Boeing (2000)
Heliotek	Aerospace PV	1960	Space	Acquired by Textron (1960), placed under common management with Spectrolab
Solar Technology International (later Arco Solar)	Residential and utility-scale PV	1975	Spectrolab spinoff	Acquired by Arco (1977), Siemens (1990), Shell (2002) and Solar World AG (2006)
SunPower	Residential and commercial PV	1985	Stanford spinoff	Acquired by Cypress Semiconductor (2000-2004) and Total SA (2011)
Solyndra	Thin film commercial PV	2005	Founder's education and employer	Bankrupt (2011)

Table 1: Notable California photovoltaic solar manufacturers

Driver	Key Customer	Period	Locational and Clustering Effects	Peak Cluster Size	Competition from Outside State	Outcome
Aerospace Niche	Space Program	1955-1970	Local demand, knowledge spillovers	4 firms (L.A.)	Weak	Niche market that grows and contracts based on government demand; firms find other businesses
Energy Crises	Utility	1974-1990	Local demand, knowledge	1 firm (L.A.)	Weak	Technological and market failure; segment disappears
Global Warming	Residential and commercial	1990-2000	(No California participation)		Strong	Led by Japanese and German firms
		2000-present	Recycling of Silicon Valley technology, human capital, investment infrastructure	20+ firms (mostly Bay Area)	Very Strong	Strong competition is bringing consolidation and exit

Table 2: Clustering outcomes for California's photovoltaic solar manufacturers



Data: Federal R&D in millions of dollars for categories 31 (solar energy) and 312 (photovoltaics) from IEA (2012); photovoltaic spending not itemized from 2003-2008

Figure 1: Federal R&D spending on solar energy, 1974-2011