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MIT-IPC-09-008

June 2009

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Innovation Systems in the Solar Photovoltaic Industry: The Role of Public Research Institutions

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Paper Submitted to Stavanger Innovation Summit "*Transforming City Regions*"
June 15-16, 2009

Abstract

The challenge of climate change provides an exciting opportunity for city-regions to pursue long-term economic development by supporting sustainability-oriented industries. Our research seeks to describe and understand the role of local systems of innovation in developing on such industry - the photovoltaics industry. We explore (a) the role of universities and national research laboratories in fostering innovation and (b) the lessons that can be applied to regions such as Abu Dhabi with vast financial resources but whose economy is strongly oriented towards a single industry (oil and gas). Our findings have implications for policies designed to support economic development and technological advancement via renewable energy technologies.

We are conducting qualitative case studies of three national contexts with varying levels of commitment to the photovoltaics industry: United States, Germany and the United Arab Emirates. In this paper, we discuss our findings from the United States, focusing specifically on California. After describing the history of the photovoltaics industry and the role of research institutions in California, we explore its implications for the Abu Dhabi region. While the Masdar Institute of Science and Technology and Masdar City are intended as anchoring institutions that can attract a critical mass of financial capital, and scientific and entrepreneurial talent, Abu Dhabi nonetheless faces a myriad of challenges.

Keywords: Innovation systems; solar photovoltaic industry; public research institutions; knowledge economies; California; Abu Dhabi.

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1. Introduction

Concerns about climate change, increasing energy demand, and energy security present enormous challenges. Dealing effectively with these issues requires the development and commercialization of early-stage technology as well as the scale up of industries based on mature energy technologies. For city regions, these broad challenges provide an exciting opportunity for long-term economic development built on new industries intended to meet those challenges.

The solar photovoltaics industry is one renewable energy technology that has attracted the attention of investors, entrepreneurs and government especially in Germany, Japan and the United States (US). Interest is growing in many city regions to develop the photovoltaics industry locally, though the strategy they follow varies according to the region's existing assets and political environment. Regions like Silicon Valley and Route 128 (Boston) in the US are established centers of technological innovation in information technology and life sciences. Germany has a strong industrial base in the southwest in addition to low labor costs and high government incentives in the new federal states in the east. Abu Dhabi, in the United Arab Emirates (UAE), has significant financial capital and a strong desire to diversify away from fossil fuels and into renewable energy.

The main goal of our research is to describe and understand the role of local systems of innovation in developing photovoltaic technology and industry. More specifically, the main research questions we aim to explore are: (a) What is the role of public research institutions (i.e. universities, national research laboratories) in fostering innovation in the solar photovoltaic industry? (b) What lessons can we learn for regions such as Abu Dhabi that are oriented towards a single industry but seek to develop new industries based on renewable energy sources? The answers to these questions have implications for policies designed to support economic development and technological advancement via renewable energy technologies. One preliminary conclusion is that, for energy city regions such as Abu Dhabi, research universities must pursue a varied set of activities to support innovation and industry development broadly. Using qualitative research methods, we are conducting case studies of three national contexts with varying levels of commitment to the photovoltaic industry: US (Boston and California), Germany and the UAE. In this paper, we limit our empirical discussion to California.

Based primarily on a historical case study of the photovoltaic industry in California, we conclude that public research institutions have played a significant, though variable, role over the 55-year history of the industry. In the earliest years, public research institutions played a minimal role in the emerging industry while in the late 1970s, national laboratories were critical for supporting industry development. As the research and policy agenda on renewable energy technologies has expanded in recent years, public research institutions have influenced industry in a diverse set of ways. We find that, in addition to expected contributions to education and fundamental research, universities support industry development in several key ways: (a) generating scientific ideas for development and commercialization; (b) attracting scientific and engineering talent to the region; and (c) fostering dense personal networks that enable the formation of startups.

In addition to examining implications for policy, our research aims to contribute to the theoretical understanding of local innovation systems. While there is ample research on the concept of innovation systems in different industries and geographical locations, the role of universities and other public research institutions, as one component of the innovation system, has not been deeply understood. Broad overviews have been presented by Nelson and Rosenberg (1994) and Cohen et al. (2002). Despite some attention to the importance of university-industry linkages to the local economy (e.g. Saxenian 1994) and formal mechanisms of technology transfer (i.e. Bayh-Dole Act), little attention has been paid to informal institutions supporting university linkages (Mowery and Sampat 2004). Relative to this work, we seek to elucidate the micro-level mechanisms through which public research institutions contribute to innovation and industry development. This research approach builds on the work of Lester (2007) and colleagues in the Local Innovation Systems Project who deemphasize the role of the university as a source of innovations to be commercialized, and instead emphasize the university as contributing to local problem solving capability and serving as open spaces for industry coordination.

The paper is organized as follows. Section 2 summarizes our research methods, data collection, and data analysis process. We then describe, in Section 3, the historical emergence of the solar photovoltaic industry in California. In Section 4 we discuss the role of public research institutions in fostering innovation in the solar photovoltaic sector using both existing literature and findings from our qualitative research. In Section 5 we draw lessons on how city regions, such as Abu Dhabi, might strategize their efforts to develop a renewable energy sector. We conclude with main findings, policy and theoretical implications, and suggestions for future research.

2. Research Methods, Data Collection and Analysis

We carried out a set of historical comparative case studies designed to trace the scientific, technological and commercial development of the solar photovoltaic industry in different locations. We chose to study California, Boston, Germany and Abu Dhabi. California and Boston were chosen because of the historical role the US has had in creating the industry. Germany has emerged as the leading nation in photovoltaics deployment and is home to many of the top photovoltaics firms. Abu Dhabi represents a region with a minimal knowledge economy but with vast financial resources and a desire to develop photovoltaic industry. In this paper we present only findings from California.

The principal mode of data collection is in-depth semi-structured interviews with firms, scientists and administrators at public research institutions, policy makers, and other actors in the innovation system. Where possible, this was corroborated and elaborated using secondary sources. We designed an interview protocol for semi-structured interviews, which was used as a guideline rather than as a rigid list of questions and items. The main issues we addressed in the interviews relate to: (1) products, technology, innovation process; (2) relationships with universities and national labs; (3) financing issues; (4) location decisions; (5) role of public policy for their specific operations; (6) labor intensity along the value chain; and (7) future trends for the company and the region. Almost all interviews were recorded. Each interview lasted between 60 to 90 minutes. We conducted 68 interviews with companies all along the value chain, scientists at public research institutions, and public policy actors: 40 interviews in California, 13 interviews in Germany, and 15 interviews in the UAE. The interviews were recorded, transcribed, coded, and analyzed using the NVivo qualitative research software package.

3. The Emergence of the Solar Photovoltaic Industry in California

California has played an important role in the solar photovoltaic industry at two points in the industry's history. The industry unarguably originated in the US, a product of the Space Race with the Soviet Union. Los Angeles, located in southern California, had been an important center of the aerospace industry since before World War II. As the California Institute of Technology (Caltech) and the Jet Propulsion Laboratory (JPL) was becoming involved in the budding space industry, photovoltaic technology was establishing itself as the standard power source for space satellites. This made the Los Angeles area a natural place for research and production of photovoltaic solar cells. In the 1970s, amidst growing interest in using photovoltaics to supply terrestrial "bulk" electricity, Los Angeles remained an important, though not the only, center of photovoltaic activity.

More recently, "clean technologies" have emerged as an important class of high technology investments alongside information technology and life sciences vying for the attention of entrepreneurs and venture capital. Silicon Valley, in the San Francisco area, has been the clear leader in developing new technologies over the past 30 years and is now engaging with photovoltaics and other sustainability-related technologies. Progressive state legislation, history of using solar technology, and an established base of high-tech manufacturing and has helped to make California a viable market for photovoltaics technologies, providing a nurturing environment for fledgling solar companies.

3.1 *Los Angeles: The Original Solar Cluster*

Shortly after the first silicon photovoltaic device was invented in 1954 at Bell Laboratories, the technology quickly found an application in powering space satellites. In 1955, President Dwight Eisenhower had announced plans for the US to launch a satellite into space, leading the US Army, Navy and Air Force to each begin formulating design proposals. When the Soviet Union successfully launched two Sputnik satellites in 1957, the sense of urgency increased. Engineers were confronted with the problem of finding a reliable power source, ideally with a high power-to-weight ratio. While the very first satellites were powered by batteries, photovoltaics quickly established itself as the standard technology for powering satellites.

The Los Angeles area is home to two key organizations in history of space exploration – the JPL[4] and Caltech. JPL's origins can be traced back to the Guggenheim Aeronautical Laboratory at Caltech. The aerospace industry began developing in Los Angeles as far back as 1909, and was the second largest aerospace agglomeration after World War I.

Photovoltaic solar cells received wide attention in March 1958 when the Vanguard 1 was successfully launched. The Vanguard 1 was the second satellite launched by the US and was powered partially by small photovoltaic cells. The Vanguard transmitted data for eight years, outlasting the two satellites that had been launched by the Soviet Union only months before and the first US satellite, the Explorer 1.

The photovoltaic industry during this time period was very small. Throughout the 1960s, the annual market of solar cells was worth about $5 to $10 million, equivalent to 50-100 kW of capacity (National Research Council 1972). Production capacity exceeded demand by over a factor of five and, with the US government as the primary customer, demand was uncertain. Throughout the 1950s and 60s only five companies produced photovoltaic cells (Wolf 1972). Hoffman Electronics was the Los Angeles company that had produced the solar cells for the Vanguard 1. Only two year earlier, in 1956, Hoffman Electronics acquired National Fabricated Products along with their patent license to the original Bell Labs technology.

One of the earliest competitors to Hoffman Electronics was Heliotek, founded by Alfred Mann, a spinoff from an earlier company created by Mann, Spectrolab[5]. Mann served in World War II as a bomber navigator and later studied at University of California Los Angeles (UCLA) where he obtained Bachelors and Masters degrees in physics. His interest in studying light led to a first job with Technicolor, a Los Angeles firm whose color film processes dominated the motion picture industry between 1922 - 1952. The Army approached Technicolor for help with light filtering for a missile guidance system but, when Technicolor did not pursue the work, Mann pursued the $11,200 Army contract by leaving the company and forming Spectrolab in 1956. Heliotek, also located in Los Angeles, applied Spectrolab's light filtering expertise for use in solar cells. Its solar cells were used in the Pioneer 1, launched in October 1958.

Other than Hoffman Electronics and Heliotek, there were only three firms that entered the market for solar cells at the time - RCA, International Rectifier, Texas Instruments. In contrast to Hoffman and Heliotek, these were established companies that had diversified into the solar cell market: RCA produced radios, International Rectifier and Texas Instruments produced semiconductors. They were not located in the Los Angeles area and all three left the market by the end of the 1960s. The relatively small and unpredictable market did not appeal to these larger firms.

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[4] JPL designed and operated the first successful US satellite, Explorer 1, which launched in 1958. Later that year, JPL became part of NASA as its primary planetary spacecraft center and went on to play a large role in later US satellite programs – designing and operating the Ranger and Surveyor satellite programs in the 1960s.

[5] The two companies were united in 1960 when both were acquired by Textron. Spectrolab still exists today and is the leader is super high efficiency solar cells.

While the first generation of photovoltaic firms focused on space applications, the second generation of firms focused on terrestrial applications. The Arab Oil Embargo in October 1973 crystallized interest in the terrestrial application of photovoltaics[6]. The growing interest is reflected in the size of the market; by 1972, the cumulative production of solar cells was only 0.6 MW but by 1980, that number had increased to 19.25 MW.

Two of the best known PV firms emerging shortly after the Arab Oil Embargo were founded in California by former employees of Spectrolab. Bill Yerkes, former President and CEO of Spectrolab, founded Solar Technology International in 1975. Ishaq Shahryar, a former Spectrolab scientist, founded Solec International in 1976. Solec International was eventually sold to Sanyo and is still in operation today. Solar Technology International was acquired by the Atlantic Richfield Company (ARCO) in 1977, was renamed ARCO Solar. For more than 10 years, ARCO Solar was the dominant solar cell company in California and one of a few of large solar companies across the United States. Going into commercial production in 1980, ARCO built the first production facility of greater than 1 MW capacity. ARCO was involved in several high profile photovoltaics projects including the first utility-scale plants, all in California: a 1MW plant in Hesperia serving Southern California Edison, a 6 MW plant in Carrisa Plains serving Pacific Gas and Electric, and two 1 MW plants in Rancho Seco serving the Sacramento Municipal Utility District. Internationally, ARCO developed partners and sold photovoltaics for off-grid applications into over 80 countries. By the time the company was sold to Siemens in 1990, ARCO Solar was the largest photovoltaics manufacturer in the world.

These firms still exist today, though under different ownership. Heliotek was merged with Spectrolab and continues to produce super high efficiency cells. Solec International continues to operate under the ownership of Sanyo. ARCO Solar was sold to Siemens who then sold it to Shell before finally being sold to Solarworld. Other than this handful of companies, there has been limited growth of the industry in Los Angeles[7].

3.2 *Silicon Valley: The High Tech Cluster of Solar Technology Today*

After 2001, there was a resurgence of PV industry activity unmatched since the late 1970s. In the early 1980s, interest in solar photovoltaics tapered off when technical progress proved slower than expected, oil prices leveled off, and President Reagan took office bringing a strong market ideology. Support from the US government drastically declined, stagnating industry growth for the next 20 years.

Two factors help to explain the timing and location of the San Francisco area photovoltaics cluster. On the demand side, Germany passed the Renewable Sources Act in 2000, establishing a cost-based feed-in tariff for photovoltaic systems. Under the feed-in tariff, the utility company is required to buy electricity generated from the photovoltaic system at a specified price over a 20 year period. In 2004, electricity from a small roof-mounted system could be sold to the utility at 57.4 Euro cents per kWh, a number greater than the estimated cost of generating the electricity. Although the German feed-in tariff was not the first government incentive program for photovoltaics[8], is offered the simplest and largest incentive. The apparent success of the German feed-in tariff in stimulating photovoltaic deployment and national industry has lead other European countries - Spain, Italy, France and others - to pass similar feed-in-tariff incentive programs.

These government incentive programs drove a large demand for photovoltaics, even though the technology could not directly compete against traditional forms of generation. Installed photovoltaic capacity was 254 MW in 2000, 1460 MW in 2005, and 5948 MW in 2008 (Solarbuzz). Because this demand materialized precipitously, dedicated photovoltaics firms - large and small – had an opportunity to capture a portion of the new market. Large solar-only companies like Suntech, Q Cells, Solarworld were able to catch up with diversified electronics companies that had previously dominated the market like Sharp, Sanyo and Kyocera.

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[6] Solar Power Corporation and Solarex were founded before 1973.
[7] One exception is Amonix which was founded in 1989.
[8] Japan started the Residential PV System Dissemination Project in 1994. California began the Emerging Renewables Program in 1998.

On the supply side, entrepreneurs and investors were looking for a new class of start-up opportunities after the dot-com boom. San Francisco was the clear leader in developing a wide variety of new technologies and, with a new market in a technology-based industry, more attention was being paid to photovoltaics and other "clean" technologies. The relevance of San Francisco reflects a drastically different image of university technology transfer that occurred in the 1980s and 1990s. Prior to this, the view of technological innovation was mainly shaped by Vannevar Bush (1945). According to Bush, innovation is a linear process where basic research preceded applied research, which in turn precedes development. Based on the success of university research in World War II, the belief was that an investment in basic research in universities would lead to technological advances downstream in industry.

The image of technology transfer became more complex after 1980. The passage of the Bayh-Dole Act, shortly followed by an increase in patent and licensing activity, drew attention to intellectual property as an a key mechanism for technology transfer. In addition, the success of Silicon Valley and Route 128 led to an interest in studying how regions could develop into entrepreneurial centers. Universities were considered an important element because of the local character of knowledge spillovers and geographically-constrained behavior of scientists. Another important element was an organized institution for investing – venture capital – which had been developing throughout the 1970s and was validated with the IPO of Genentech in 1980. Recent developments in the photovoltaics industry in Silicon Valley are best understood with this new imagery of technology transfer in mind.

San Francisco is home to several high-profile photovoltaics firms including Sunpower, Nanosolar, and MiaSolé. A review of Dun & Bradstreet data shows that there are 46 solar cell manufacturer establishments in California and, of these 46, twenty are located in the Bay Area, greater than the number of establishments in any other state. While impressive, we believe this number still underestimates the concentration of solar firms in Silicon Valley. We are aware of several dozen solar startups in the area and, according to those we interviewed, there are at least 100 startups that have received funding and many more that are seeking funding.

The Bay Area has access to three types of assets that have helped in developing a local photovoltaics industry. First, with a long history of technology entrepreneurship, there is an established base of professional talent including: venture capital, entrepreneurs & managers, and attorneys. Second, past industries that have been successful in the region - the semiconductor and computer industries – developed local competencies in engineering and high tech manufacturing that are also applicable to photovoltaic technology. Third, California's progressive stance on energy and environment has led to a suite of legislation, including the first statewide solar incentive program in the US, supportive of the photovoltaics industry.

Silicon Valley's base of entrepreneurship assets is helpful for photovoltaics startup firms. The photovoltaics industry is bifurcated between firms backed by a large oil or electronics company and firms dedicated solely to solar photovoltaics technology. The former are companies that have significant financial and human capital developed from other lines of business and are diversifying into the solar market. They tend to focus on more established technologies that can be commercially produced with little development time, a strategy that cannot be imitated by many potential competitors. The research needs of large companies are driven by their technology and product strategy, which follows a market-oriented logic. Research and development must have a fairly narrow focus and the firm can afford to employ many scientists and engineers to pursue proprietary research. Thus the role of universities is limited to attracting and developing a technical workforce and solving specific problems that may be important to the industry but are not of strategic importance to the firm.

Firms that are dedicated to photovoltaic technology tend to begin as startups that develop a more advanced technology. For these firms, there has been a very different role for the university. These firms focus on advanced technologies that are years away from commercial production and that carry non-trivial development risk. An organized system for investment, involving angel investors and venture capital, can offer capital and managerial expertise to complement an innovative technology.

In addition to entrepreneurship assets, Silicon Valley has provided resources from other predominant industries – the semiconductor and computer industries. In a state where manufacturing plays a small role in terms of gross state product, Silicon Valley, along with the Los Angeles area, is an important center of high tech manufacturing. Because the photovoltaic and computer industries both work with semiconductors, the physical and organizational infrastructure that supports one also supports the other. The production of both technologies involves the manipulation of silicon wafers. Thus, equipment manufacturers that serve the semiconductor industry could also serve the photovoltaic industry, engineers with experience in the semiconductor industry could also work in the photovoltaic industry and firms with existing supply channels for raw silicon could obtain silicon for photovoltaics. The benefit of a common set of knowledge applies to other photovoltaic technologies as well; the deposition of semiconducting material for flat-panel displays is applicable to the production of thin-film solar cells.

The experience of Sunpower, one of the industry's leading firms, illustrates the role of Silicon Valley's entrepreneurship and industrial assets has played in developing the photovoltaic industry in the region. Sunpower was founded in 1985 by Richard Swanson, a former Stanford professor. In 1989, Swanson took a sabbatical to develop the company with Series A funding from an investor nearby and, in 1991, left his university position to pursue Sunpower full time. Throughout the 1990s, Sunpower sought out niche PV applications with customers that required very high efficiency cells and were willing to pay the high costs – Honda, NASA. As a small startup subsisting on small amount of funding from two venture capital firms in the Bay Area, they could not compete in the bulk terrestrial market against large firms that had diversified into the area - Sharp, BP, Shell, Kyocera, Siemens – and that could endure years of losses before finally turning a profit. Sunpower was a small, high tech firm that was strongly research oriented. Swanson had difficulty of obtaining large investments, describing his efforts as "talking to venture capitalists and banks until he was blue in the face." In 2000, he found a strategic investor, Cypress Semiconductor that invested $150 million and provided its expertise in semiconductor manufacturing. Sunpower began full commercial production in 2004 and went public in 2005.

Although numerous industries have benefitted from the Silicon Valley's entrepreneurial system and manufacturing and engineering expertise from the semiconductor industry, the photovoltaics industry has benefitted from the active influence of the government. This is especially true for renewable energy, which is still more expensive than traditional non-renewable technologies (e.g. coal, natural gas). Here California seems to enjoy an advantage relative to other US states. California is known for its progressive environmental and energy policies which make it attractive for photovoltaics. In the past it has demonstrated interest in solar technology – installing the early ARCO power plants in the 1980s as well as nine solar thermal plants built by Luz International between 1985 and 1991. The state also has a set of policies that encourage the installation of photovoltaic systems. These factors create a nearby source of demand that can nurture new solar cell manufacturers.

Perhaps the most important of California's policies are direct incentives. The first statewide incentive program in the US was the Emerging Renewables Program, which was authorized in 1996 and began in 1998 as one component of the deregulation of the California energy market. At its inception, the program offered a rebate based on the capacity of the system ($3 per watt). In 2001, it was augmented by the Self-Generation Incentive Program that targeted large photovoltaic systems. Both these programs ended and were replaced by a more ambitious incentive program in 2007 as part of the California Solar Initiative.

Another important incentive is the flexible electricity rate structures. The standard residential plan follows a five-tier rate structure with a "baseline" rate of about $0.11 per kWh and a fifth-tier rate of about $0.37 per kWh. Homeowners can also elect to use a time-of-use electricity rate in which the peak summer rate is about $0.29 per kWh compared to an off-peak rate of about $0.10 per kWh. Compared to a flat-rate structure, these rate plans increase the relative attractiveness of solar electricity.

Other features that enhance the attractiveness of the California market for solar PV include the California Renewable Portfolio Standard (RPS) and federal and state income tax credits. The California RPS mandates that 20% of the all electricity generated must come from renewable sources by 2010. The state income tax credit of 15% first went into effect in 2001, supplementing the federal tax credit which was only 10% at the time. In 2005, the federal government established a 30% federal tax credit, obviating the smaller state tax credit.

4. Past and Current Role of Public Research Institutions in the Solar Photovoltaic Industry

The role of public research institutions has been different for each generation of PV firms. For the first generation of firms that supplied space applications, public research institutions played a minor role in developing solar PV technology. For the second generation of firms that were founded with the expectation of a large terrestrial market by the 1980s, national labs led the effort to develop the technology for the industry. For the third generation of firms that were founded during the modern era of technology transfer, universities provide a source of scientific ideas, a nexus of personal networks, and source of technical expertise.

In the 1960s, more than $50 million had been spent on R&D for space solar cells (Perlin 2002) and universities were undoubtedly involved at the time. The National Science Foundation (NSF) was the lead government agency for solar energy between 1952 and 1974[9] and between 1952 and 1970, approximately $100,000 was spent on "basic" solar research per year (Strum and Strum 1983). The NSF authorized increased research spending between 1971 and 1974: $300,000 in 1972, $800,000 in 1973, and $2.4 million in 1974. Recipients of NSF funds included Martin Wolf at the University of Pennsylvania, Joseph Loferski at Brown University, and Karl Boer at the University of Delaware. However, because of the space market was small and unpredictable, firms had little incentive to incorporate recent scientific advances. Much more effort went into reliability testing, solar array design and radiation resistance than in developing new materials or increasing solar cell efficiency.

For the firms founded after 1973, the main challenges were twofold: (1) "downgrading" the cell design of space cells with the goal of making terrestrial cells much less expensive and sacrificing only a little cell efficiency, and (2) setting up cost-effective commercial scale production. This perspective was established at the Cherry Hill Conference, which, taking place only weeks after the start of the 1973 Arab Oil Embargo, convened representatives from government, industry and academia. Attendees laid out the fundamental concepts of the US photovoltaic research program, outlined a 10-year research program including milestones and called for $295 million crystalline silicon technology.

The plan was premised on the belief that the primary challenge was ensuring adequate investments in the technology (DOE 1982, Margolis 2002). The perceived solution to this problem was government purchases to ensure adequate demand until commercial markets developed – first in remote applications and later in grid-connected applications (Hart 1983). This approach had apparently worked for the US semiconductor industry only years earlier. In addition, a focused R&D program would help to improve the technology to a point where it could be commercially produced profitably. photovoltaics was seen as a proven technology for small applications, but needed a small development boost to be competitive with large-scale utility use. It was believed that it would "cost $500 million to achieve its goals of a $500-per-kilowatt manufacturing price by 1986"[10] (Herman 1977: 87). Industry was to be involved as much as possible so that what was learned from the project could be directly applied to production.

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[9] In 1974, that responsibility was handed over to the Energy Research and Development Administration, the predecessor of the Department of Energy.

[10] For reference, the Department of Energy (and its predecessor the Energy Research and Development Administration) had spent this much on research by 1981. According to Paul Maycock, the average module price was $30 / Watt, or $30,000 per kw in 1975. And in 1986, the average module price was $5 / Watt or $5,000 per kw.

The primary research program that resulted was the Flat Plate Solar Array (FSA) Project.[11] Organized by JPL and beginning in 1975, its goal was to achieve the widespread commercial use of PV by reducing the cost of modules to $0.50 / watt, with a 10% efficiency, and 20 year lifetime. The FSA Project was notable for helping to establish quality standards. JPL purchased solar cells from manufacturers but, to qualify for the government purchase, manufacturers had to meet certain performance requirements. There were five "blocks" of purchases over a six-year period, each block with higher standards. Once solar cells were purchased, they were tested further for exposure to temperature and humidity in the lab and in the field. In addition, 26 Project Integration Meetings drew together hundreds from industry, academia and government to discuss findings and ongoing research. University scientists were involved in the JPL project but their research was oriented towards meeting project milestones.

During this period, the role of public research institutions was derived from the national photovoltaics research program. The original goal of the program was to make solar cells a commercially viable technology. Thus, the goal of the program was applied R&D. Though JPL was not the only government lab involved[12], it did have a lead role in coordinating the best-known federal program, the FSA Project. University researchers were involved but their role was in support of the overall program goals. Research into more advanced concepts did occur, but were not at the forefront of industry developments.

After 1980 and particularly after 2001, universities have played a greater role in developing the California PV industry. Stanford University is credited for helping create Silicon Valley about 40 years ago, so in a sense can also be attributed to have some influence on every technology developed in the region, including PV. It was influential in the semiconductor and computer industries in their formative years, helping to provide foundational resources for the PV industry (Arthur 1990). More specifically, however, universities have played a role in developing scientific ideas, in attracting individuals with technical expertise, and in providing access to networks of entrepreneurial resources.

Perhaps the most basic mission of the university and national labs is the generation of new scientific findings (Nelson 1986). While some of these findings will be "basic," others will be commercializable. "Basic" scientific findings may eventually lead to "applied" discoveries later on, and applied research provides grist for the entrepreneurship mill. Public research institutions provide a necessary input for an emergent technology-based industry, and variation in the innovations produced can provide firms with a source of competitive advantage.

Research conducted locally can be helpful for encouraging subsequent research and commercial activity (Jaffe et al.1993, Zucker et al. 1998). California lost one center of photovoltaic research in 1986, when research leadership for crystalline silicon was transitioned from the JPL to Sandia National Lab in New Mexico. However, California gained another research center in 2004 when Steven Chu (currently the US Secretary of Energy) assumed directorship of Lawrence Berkeley National Lab (LBNL) located in the San Francisco area. Chu called the energy "the single most important societal problem that science and technology must face" and sought to focus the lab's resources in this direction. This is borne out in an analysis that we conducted on academic journal publications (Vidican et al. 2009). Until the 1990s JPL generated approximately 50% of all publications on solar energy emerging from national labs. LBNL is currently the primary national lab involved in solar related research in California, claiming more than 60% of research from national labs in California. Also, university involvement has also increased between 1995-2008, compared to the 1975-1985 period.

Local public research institutions also provide vital resources for startup firms which are intrinsically fragile. First, they help provide scientific and technical expertise which serve as inputs to the PV industry (Anselin et al. 1997). They help to create a vibrant intellectual community that attracts talented individuals to the area and compels them to stay. For solar startups, universities can provide scientific advisors and recent PhD graduates with very specific skills that can contribute to technology development. Second, universities also provide a

[11] It was originally named the Low Cost Silicon Solar Array Project and also the Low Cost Solar Array Project
[12] Others include the Solar Energy Research Institute, Sandia National Lab, Brookhaven National Lab, and NASA's Lewis Research Center.

setting where the resources necessary to form a startup can be accessed through interpersonal and interorganizational networks (Owen-Smith and Powell 2004). A scientist with a new idea can meet investors, scientific advisors, consultants, managers, and attorneys through university connection. These networks not only enable an introduction, but shared affiliation with other actors can positively prime the relationship.

5. Creating Innovation Systems for the Solar Industry in Abu Dhabi

Abu Dhabi is one of the seven emirates in the UAE, concentrating more than 90% of the country's oil and gas reserves and 10% of the world reserves. Following global concerns on climate change, oil prices, and economic sustainability Abu Dhabi has recently declared an interest and commitment to transform its economy from an oil- and gas-based economy to a knowledge economy focused on solar and other renewable energy technologies. The vision is for an integrated approach for the development of the solar industry at all parts of the value chain, from technology innovation and development to cell and module manufacturing to local market deployment and export markets.

Despite these aspirations, the Abu Dhabi solar industry is in its earliest stages and these is uncertainty over how and if the local industry will develop. Although we were able to identify 77 solar-related companies and other interested organizations across the UAE, their activities have been uncoordinated. The largest project currently under way is the Masdar Initiative - a multifaceted development funded by the national investment company Mubaddala, comprising of a net-zero carbon and zero waste city (Masdar City), research university (Masdar Institute of Science and Technology - MIST), green industry cluster, investment group, and other units.[13] Masdar City and MIST are intended to serve as an anchor for attracting and retaining talent investment, and established companies to the region.

Companies, scientists, and policy-makers that we interviewed pointed to a number of challenges they faced in developing the incipient Abu Dhabi solar cluster: (1) lack of supportive government policies; (2) limited and inconsistent R&D funding; (3) limited venture capital; (4) a small scientific research community; and (5) a lack of photovoltaics-related industries.

Government regulations intended to support industry development have not yet been formulated. Abu Dhabi faces an uphill battle because electricity consumers already enjoy highly-subsidized electricity rates and, as a general rule, are not sensitive to sustainability concerns. One idea under consideration is to focus on large utility-scale deployment that can be encouraged from the top-down. Similarly the combined use of a Renewable Portfolio Standard (RPS) and a feed-in tariff will encourage electricity-providers to install solar systems. An RPS target of 7% by 2020 has been announced in January 2009 but has yet to be formalized into law. Consumers also have little sense of the cost of generating electricity because different segments of the population pay different rates for electricity; the subsidized rate for locals is $0.008/kWh while for non-locals is $0.041/kWh. These low rates provide little incentive for consumers to install photovoltaic systems.

A central element of the Silicon Valley innovation system is the research community of universities and national laboratories which help to generate ideas, produce scientists and engineers, and facilitate the formation of startups. In Abu Dhabi, few elements of the university-based system of innovation are in place. With the exception of the recently established MIST, there are no strong graduate level universities or research laboratories. Research funding is extremely limited and there is a minimal presence of venture capital and community of entrepreneurs to help develop innovations originating from the university.

Another major challenge for the development of a new industry in Abu Dhabi is the lack of existing industry and manufacturing experience. While the San Francisco area has thrived over the years due to its diverse industrial focus and its ability to quickly adapt to changes in the market, by shifting knowledge and resources into new related industrial fields, the economy of the UAE is driven by the extraction of natural resources (oil and gas), providing little diversity and flexibility in intellectual resources.

[13] More factual information on the Masdar Initiative project can be found at: www.masdar.ae.

The transformation of the Abu Dhabi region into an innovative center of renewable energy technologies will require time. Although the architects of the Masdar Initiative recognize this, they must demonstrate a long-term commitment through ongoing support for research and education in science and technology, and enactment of government policies to support industry. Early emphasis on research and education could begin the lengthy process of developing a synergy between different institutions. Also, building professional and industry communities is critical for supporting close networks of communication and knowledge transfer in the industry.

Further research is needed to explore what development strategy best suits the city region of Abu Dhabi (e.g. focus on upstream or downstream in the value chain). Abu Dhabi could pursue an innovative-centric strategy by investing in R&D facilities, developing strategic areas of collaboration between academia and industry, while also directing significant resources towards fundamental research.

6. Conclusions

While Los Angeles area was the birthplace of the photovoltaics industry, most of the current activity is located in the San Francisco Bay Area. The involvement of public research institutions in developing the photovoltaics industry has varied overtime. During the 1970s, when it was believed that only modest R&D investment would be necessary to make the technology commercially viable, JPL coordinated a research program that involved academic and industry scientists. Today, when more advanced photovoltaic technology is being pursued, universities are playing a larger role: generating innovation, providing entrepreneurs access to entrepreneurial networks, and staffing and advising startup firms.

These findings suggest two options for MIST in helping to develop a solar industry in Abu Dhabi. One is a technology development model in which MIST administers a directed development program and coordinates industry and the research community. This is the role that JPL played when it ran the FSA project. The second option follows the roles of Stanford University and LBNL in San Francisco. While this model seems to be the modern paragon of a local innovation system, there are immense challenges to imitating Silicon Valley. The challenges would include: (a) attracting entrepreneurial talent and nurturing conditions for skill development and knowledge production locally; (b) creating an institutional infrastructure in the form of venture capital, research facilities, regulatory support for the industry, and networking opportunities; (c) building on the development of Masdar Initiative as an anchoring institution for the industry.

The development of a solar cluster in city regions such as Abu Dhabi is a process that will evolve overtime and will require concerted efforts on multiple institutional and organizational levels. In striving for a Silicon Valley model of local innovation while recognizing the difficulty of the task, perhaps a first step is to follow the JPL model of directed development. This would begin to attract industry and scientists to the region, setting the foundation for the more decentralized Silicon Valley system.

These findings point to several areas for future research. First, an examination of Germany's history with the photovoltaics industry would be insightful. The German government is currently playing a far more active role than the US government in developing the industry. Their approach in supporting the photovoltaics industry includes: the feed-in tariff which motivates deployment, government-supported research in organizations such as the Fraunhofer Institute, and generous incentives for firms locating facilities in the former East. Research in this direction may offer an intermediate industry-development model that has a greater role for government than the Silicon Valley model but broader technological focus than the JPL model.

Second, major economic and industrial transitions such as those in the UAE, need to be carefully examined to better assess the local environment for innovation and to develop strategies for supporting new industry creation. Existing theories of innovation cannot fully explain how innovation systems evolve and industry clusters emerge in different environments where the starting conditions as well as the cultural aspects related to business practice vary from the more advanced knowledge economies. To shed more light on the processes by which industry clusters are being created and economic transitions take place, more in-depth research on the socio-economic and institutional environment is required, as well as comparative research case studies of countries that attempted similar economic transformations.

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