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Solar Energy Innovation and Silicon Valley

Daniel M. Kammen*

[a] Energy and Resources Group, University of California, Berkeley, USA
[b] Renewable and Appropriate Energy Laboratory, University of California, Berkeley, USA
[c] Goldman School of Public Policy, University of California, Berkeley, USA

Abstract. The growth of the U. S. and global solar energy industry depends on a strong relationship between science and engineering innovation, manufacturing, and cycles of policy design and advancement. The mixture of the academic and industrial engine of innovation that is Silicon Valley, and the strong suite of environmental policies for which California is a leader work together to both drive the solar energy industry, and keep Silicon Valley competitive as China, Europe and other area of solar energy strength continue to build their clean energy sectors.

Keywords: Phovoltaics; innovation; technology transfer; green jobs

THE DEVELOPMENT OF COST-COMPETITIVE PV TECHNOLOGY FOR GLOBAL DEPLOYMENT

The sun has been described as “that highly convenient and free fusion reactor in the sky, which radiates more energy to the Earth in a few hours than the entire human population consumes from all sources in a year.”

Plugging in to that free fusion reactor has been the tricky part. While initial material science and technical challenges have largely given way to financial and business challenges, building the solar energy industry from an interesting niche market to a major part of the global energy mix – which is needed to address climate change – remains a challenge. Technically, the direct conversion of photons from the sun into energy in the form of electrons, or photovoltaics (PV), has come a long way since the first panels of PV cells were used to power NASA satellites; the price of a panel has dropped dramatically, even as their power output has gone up. And the potential of PV is enormous[1,2]: solar panels, paired with batteries to enable power at night, can produce several orders of magnitude more electricity than is consumed by the entirety of human civilization. Alternatively, the panels can be put on a homeowner’s roof and hooked up directly to the existing electrical grid; any excess generated is sent to the grid, while any time the homeowner’s demand exceeds the capacity of the panel, the household simply draws upon the grid. In effect, the electrical grid acts as a giant battery.

Many innovative approaches are being tried, in some cases drawing upon the experiences of Silicon Valley when it comes to start-ups, financing, and the introduction of new technologies. What is taking place in Silicon Valley and beyond to make this vision possible? What role can this community play in advancing laboratory research and policy and market innovation?

Based in Mountain View, California the major company Solar City, is one example of innovative thinking. The firm makes a case for a business model that is quintessentially Silicon Valley in nature. Instead of simply forecasting when solar energy will be ‘grid competitive’ (forecast to be between now and 2020 across virtually all of the United States), Solar City is one of a handful of companies that have bypassed the simple sales-only model. Why simply buy the hardware? Instead, Solar City will place panels *they own* on your roof, where you are leasing space to the company, and buying power. SunRun and Sungevity are also aggressive and innovative competitors in this space, that all promise to lower your residential utility bill *the first month.*

Such thinking comes just in time for a promising technology. In fact, in a recent regional assessment of the potential of solar energy we found that with a realistic model of the utility grid we found that with only a conservative view of innovation in the solar energy sector, photovoltaics alone could provide over one third of the total energy across western North America [3]. This result, using the SWITCH energy system capacity expansion we use in my Renewable and Appropriate Energy Laboratory [4] highlights both the potential of solar energy, but also

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* Correspondence to: kammen@berkeley.edu; 310 Barrows Hall, University of California, Berkeley, CA 94720-3050: T: +1-510-642-1640

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the need for dramatically accelerated innovation to move to the entirely clean energy economy that will be needed by mid-century.

To meet the long-term greenhouse gas (GHG) mitigation targets of 80% reductions from the 1990 baseline by 2050, solar energy can play a key role in decarbonizing electricity generation [5,6,7,8]. Solar PV technology with terawatt (TW)-scale deployment has long been recognized as an effective tool to mitigate climate change [32,10]. As shown in Fig. 1, effective energy policies in mitigating energy-related CO_2 emissions will have to accommodate the developing countries' growing needs for affordable energy sources. Therefore, it is imperative for the sustainable cost of PV technology to continue to decline for deployment in both the developed and developing countries.

The progress of developing and deploying PV technology can be greatly impeded by market failures associated with innovation and carbon emissions [11]. Policy intervention, mainly in the form of public R&D spending ("technology-push") and deployment targets and incentives ("demand-pull"), is necessary to address these market failures. As shown in Fig. 1C, energy policies, aiming at the development of PV technology into a globally affordable energy source, are essential for deploying clean energy and mitigating climate change on the global scale. These innovations require sustained performance improvements and cost reductions [1], and a vision of the widespread deployment of the most efficient use of the cleanest fuels [7].

THE UNINTENDED CONSEQUENCES OF ECONOMIES OF SCALE DURING 2011-2013

The conventional PV learning curve – a simple relationship that shows roughly a 20% reduction in solar cell costs for each doubling of total global manufacturing -- model for c-Si PV modules (Fig. 1C) has been widely

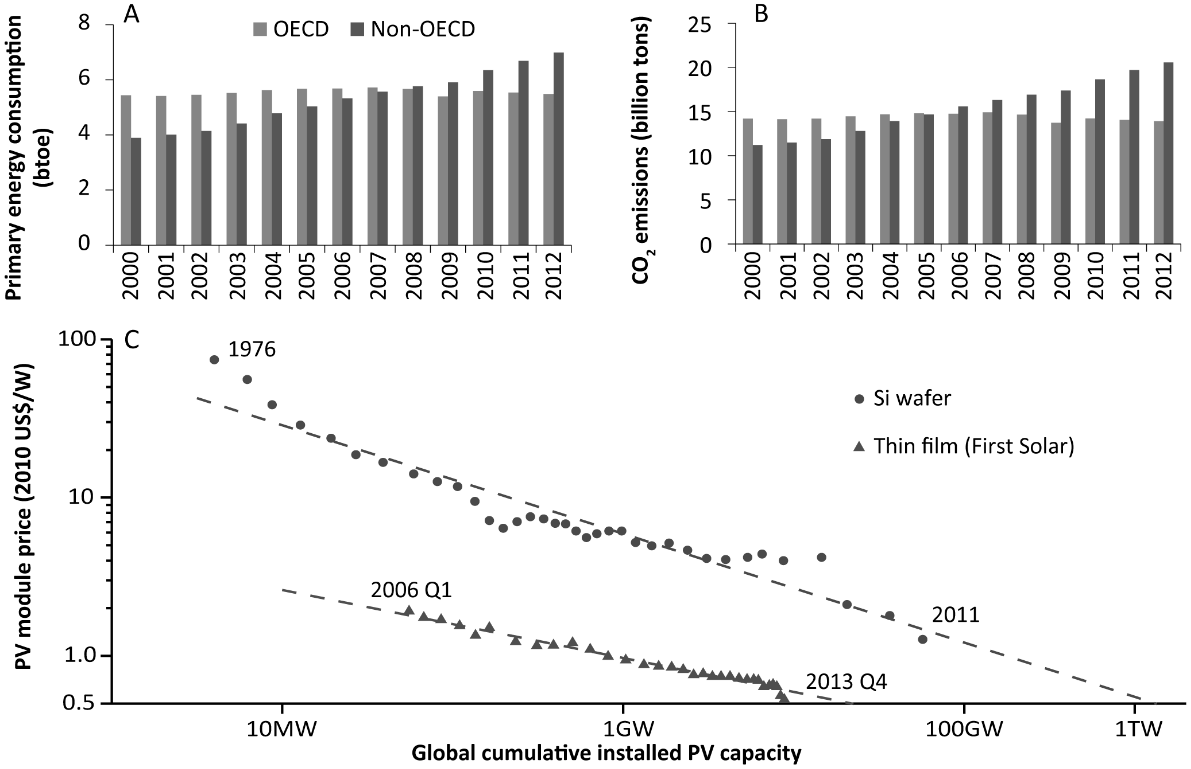

FIGURE 1. Meeting CO_2 emission targets requires further cost reduction in PV technology. The Organization for Economic Co-operation and Development (OECD) countries (in blue) and the non-OECD countries (in red) have exhibited opposite trends in primary energy consumption (A) and related CO_2 emissions (B) over the past decade. The primary energy consumption is measured in billion tons of oil equivalent (btoe). For example, with a population of 1.3 billion, China's energy-related CO_2 emissions have more than doubled from 3.4 billion tons in 2000 to 9.2 billion tons in 2012. The cost of PV technology has been decreasing steadily with increasing cumulative installations (C): the learning rates for Si-wafer PV modules and First Solar's thin film modules are 21.1% and 13.8%, respectively. All prices are inflation-adjusted to the 2010 U.S. dollars. Sources: BNEF [12], BP [13], and First Solar [14].

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referenced to support policies that rely on a cost-reduction strategy through rapid market expansion, where the average selling price (ASP) of PV modules is projected to decline with increasing cumulative installations [1,9,15]. As the market grows, production of PV modules benefits from both economies of scale and "learning," where accumulated operating experience leads to innovation and cost reductions through both learning-by-doing and learning-by-searching [16]. However, the learning rate (LR), cost reduction per doubling in cumulative installed capacity, is known to vary depending on the timeframe of the regression analysis, and this uncertainty in LR will significantly affect the projected timing and cost of reaching the cost-reduction milestones [17,18] and GHG mitigation targets.

In a recent study [19], we estimated that an annual market size of 56 TW and an estimated learning investment of US$ 25 trillion are required to reach the target module price of $0.5/W as set by the U.S. SunShot Initiative [20,3] if the cost reduction is assumed to be driven by only economies of scale. The policy implication is that "demand-pull" policies focusing on further market scale-up is likely to be unrealistic given the total market potential and the most expensive approach to achieve the SunShot goal. This viewed simply as a continued market expansion, in fact depends on a steady stream of innovations – some technical, some market and finance based, and some social and political. A careful look reveals that a number of lead actors, Germany, Silicon Valley, California and other municipal governments, and a growing global manufacturing sector play key roles in this 'momentum of innovation.'

What does look like? Each jurisdiction has set its own incentives and subsidies for clean energy deployment – a marker requirement for renewable energy in California, a special tariff to reward solar in Germany, and so forth.

The "learning" component in the conventional model is reflected in the strong correlation between market size and innovation for c-Si PV technology [19]. We formalize the overall mechanism underlying this phenomenon as market-driven innovation: the interaction of learning-by-doing, market expansion and increased commercial value. An expanding market with growing revenue supports and encourages manufacturers' R&D activities, and incentivizes commercialization of important laboratory research results [21].

A rich body of work exists where scholars have tried to understand the roles of innovation bringing new products into the market, and of the impact of economies of scale (price reductions due to greater efficiency of manufacturing) in the cost reduction of PV technology. It is important for the policy community to recognize that the primary driving force underlying the reduction in PV module prices has evolved over time, from innovation focused on improved module efficiency in the early stage of PV technology, to economies of scale [22,23,24], which exhibits diminishing returns with scaling. Today we are in a phase of the PV industry where manufacturing innovations, often of technologies developed in Silicon Valley but brought to production scale across the globe are driving further module cost reduction. The global PV market has expanded from 0.3 GW in 2000 to 38 GW in 2013 [25], and this scale-up has gave birth to GW-scale PV manufacturers, which could turn out to be an unintended barrier for new innovative technologies especially when situated in a market with serious oversupply problems. This scale-up brought an overcapacity in PV module production that caused PV modules being sold at unsustainably low prices. This imbalance and pushed almost all major PV manufacturers into financial losses in 2011 and 2012 (Fig. 2). Interestingly, while the huge ramp-up in manufacturing resulted in smaller and smaller (and then negative) profits for solar energy producers – many of whom are based in China – places that are also expert in building overall

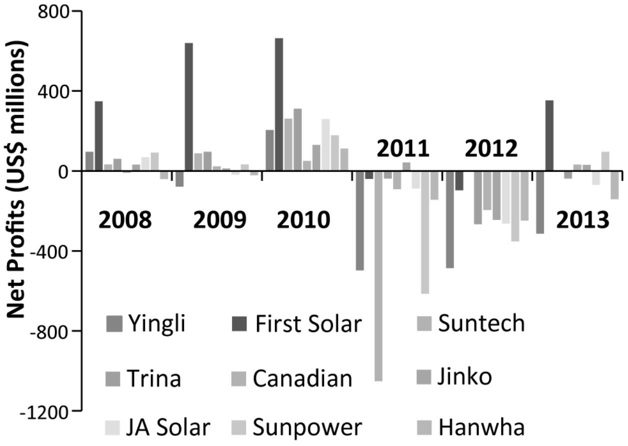

Fig. 2. Net profits (losses) of 9 major U.S.-listed PV manufacturers during 2008-2013. The 2013 financial results have shown signs of industry-wide recovery from the dark periods during 2011-2012. Source: U.S. SEC [27].

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energy systems and financial models – both hallmarks of Silicon Valley firms – have profited from the falling module prices. As one example, the overall cost of solar energy systems a decade ago was dominated by the solar panel, now the 'balance of systems' (the power inverter, electronics, and other ancillary parts of hardware) now dominate the cost of the system.

This overcapacity situation made capital-intensive investment in expanding production capacity unattractive to investors. Lacking the opportunities to scale up production, early-stage PV companies with innovative technologies are forced to compete with incumbent GW-scale manufacturers at unsustainably low module prices. As a result, the industry saw of smaller PV manufacturers facing bankruptcy, or acquisition.

This process, in turn, lead to further tightening of the capital flows into the industry, for a time causing some analysts to see a pessimistic future for solar (reference). This negative view still persists, but has eased, part because of the new wave of both technical and deployment innovations. Today, thin-film solar panels with the potential for greatly reduced costs, new financing innovations so that in many places shifting to leased solar panels can save property owners who switch to solar in the very first month of installation [25].

AN INNOVATION-FOCUSED POLICY FRAMEWORK FOR A SUSTAINABLE PATH TOWARDS AFFORDABLE PV TECHNOLOGY

These waves of innovation highlight the need for an aggressive, sustained, commitment to innovation. Here we show a conceptual model (Fig. 3) developed in our recent study [19] that clarifies the dynamics among innovation, manufacturing, and market, and use the U.S. as a case study to explain an innovation-focused policy framework for building a sustainable PV industry on the national level.

A set of clear-targeted and long-term deployment policies are essential in the reinforcing dynamics among innovation, manufacturing, and market. Firstly, clear, long-term deployment policies can reduce market uncertainties and encourage more efficient industry-wide consolidation, which contributed to the improved financial performance of major PV manufacturers in 2013 (Fig. 2). Secondly, as part of the market-driven innovation mechanism, a long-term and expanding market also incentivizes commercialization of important laboratory results through channels such as venture capital (VC) funding.

Manufacturing activities are one important source of innovation through learning-by-doing. Moreover, the corporate R&D investment from PV manufacturers also enables innovation through learning-by-searching. As the manufacturers' competitiveness increasingly relies on cost reduction through innovation, it is possible for a nation to use innovation to anchor manufacturing activities, and thus form a reinforcing dynamics between innovation leadership and manufacturing leadership.

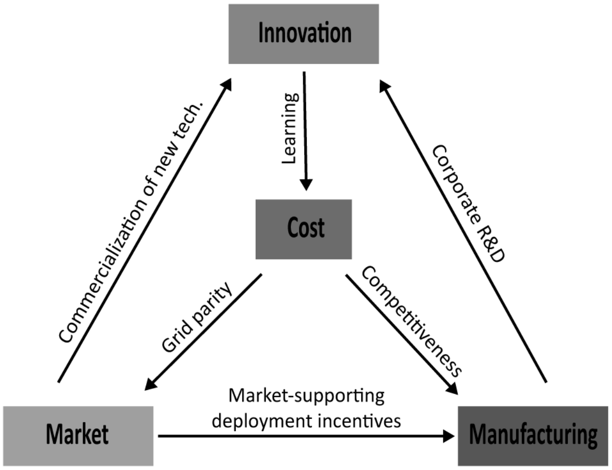

FIGURE 3. The conceptual model for building an innovation-focused and sustainable PV industry. Utilizing the reinforcing dynamics among innovation, manufacturing, and market, a set of long-term, innovation-focused, and market-supporting policies can lead to a nation's technology leadership and help reduce the cost of PV technology for global deployment.

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The optimum structure of the PV manufacturing sector will largely depend on trade policies. Without trade barriers, surviving international competition would require economies of scale and thus a critical size of the manufacturing cluster, where a handful of giant PV manufacturers may comprise most of the market share. On the other hand, the ongoing trade tariff will ease the international competition, and policymakers could promote a national PV manufacturing sector with lower market concentration. Giant incumbent manufacturers present large cost disadvantages and risks for start-up manufacturers, whose innovative technologies are yet to be scaled up. In a segmented global PV market, a national PV industry with low market concentration could be an additional boost to innovation during the next 7 to 10 years of an innovation-driven phase, where the VC community in the Silicon Valley could see more opportunities in finding commercially viable, innovative PV startups.

Elevated level of public R&D funding and focus on technological development in PV are the other central piece of this conceptual model. "Demand-pull" policies will likely face leakage problems on the national level in a globalized PV value chain. Therefore, directly injecting resources to innovation by public R&D funding should play a stronger role. The IEA study [28] identified the need to more than double the public R&D funding, benchmarking R&D budget as 10% to 20% of deployment cost.

Innovation itself can be made more cost-effective with innovative R&D models, such as establishing a national program aimed at promoting R&D collaboration and technology transfer among PV manufacturers. For example, the U.S. funded a shared R&D center in 2011 through the PV Manufacturing Consortium, which borrowed the pre-competitive R&D model from the semiconductor industry.

An open data model for the PV industry could be adopted by the international community to attract more policy and market research. Various data collection efforts (from organizations like IEA to companies like BNEF) already exist; however, variations in data and methodologies are common. It is therefore useful to compile and continuously

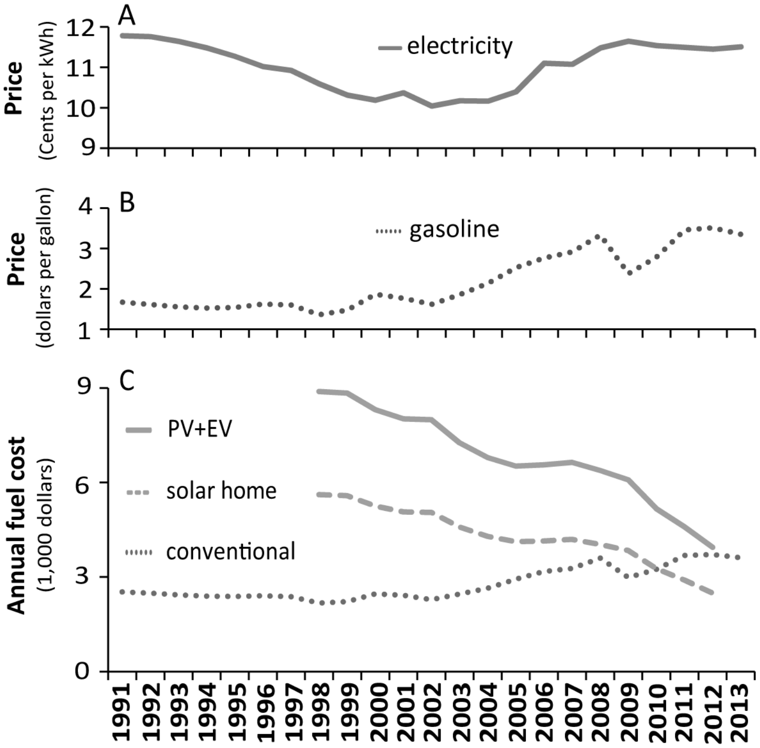

FIGURE 4. Evolution of the cost of meeting home energy and transportation needs through conventional energy supplies and a solar home/electric vehicle (EV) combination. The year-to-year retail price increases of electricity in the U.S. residential sector (A) and unleaded regular motor gasoline (B) have been as high as 10% and 30%, respectively. The cost comparisons (C) of the average US household is presented for total annual demand of 12,000 kWh electricity and 2 vehicles with 10,000 miles travelled each, using either a combination of conventional grid-based electricity and gasoline (purple dot line) or a home outfitted with a rooftop solar array and all-electric driving (orange line). Electricity consumption for electric vehicles adds about another 58% on top of home electricity consumption (orange dashed line). The capital cost of conventional or electric vehicles is omitted. The PV electricity cost is calculated from the median installed prices of residential PV systems in the U.S., with discount rate, service lifetime, and capacity factor at 5%, 25 years, and 0.2, respectively. All prices are inflation-adjusted to the 2010 U.S. dollars. Source: LBNL [31] and EIA [32].

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update an official dataset for the key metrics in the PV industry with well-documented methodologies. Making this dataset publicly available will greatly reduce the cost and time for conducting policy and market research. A richer set of analyses and opinions will be valuable for decision-making in both the government and industry, and accelerating policy and business innovation that address the soft cost of deploying PV technologies [29].

These efforts are seen today and putting PV technology on a path to become cost-competitive with conventional electricity sources in under a decade [20,3].

ENTERING A CLEAN ENERGY ERA

Figure 4 highlights the evolving economics of PV electricity in the U.S. residential sector over the past two decades from three sources of price changes: electricity, motor gasoline, and residential PV system. With the remarkable cost reduction in PV modules (Fig. 1C) and soft cost, distributed PV energy ownership, which powers homes and all-electric driving, becomes less costly (Fig. 4C) and approaches the cost of a conventional household using grid electricity and gasoline vehicles. Furthermore, self-production of energy could help U.S. households to mitigate price fluctuations in energy consumption (electricity, natural gas, and gasoline). A recent IEA report [30] found that the inflation-adjusted capital expenditure in oil, gas, and coal supply chains has more than doubled between 2000 and 2013. The energy price fluctuation is projected to turn into a steady increase in future energy costs, as fossil fuels become increasingly more capital-intensive and expensive to extract. This process would not have been possible without the confluence of a number of forces, many of which are present in Silicon Valley: university and industry research hubs tied closely to industry; mixtures of State and Federal support; and a suite of state policies that strongly encourage different aspects of the solar energy deployment.

In particular, California's Silicon Valley is world-famous for its prominent venture capital eco-system and is the global powerhouse for innovations. In an innovation-focused phase of the PV industry, energy policies are set to reward innovations enabling a cost-efficient path to sustainable PV technology, which could be deployed globally on the TW-scale. In this sustainable business environment, the VC community can profit from finding and commercializing these PV innovations.

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