Historical Case Studies of Energy Technology Innovation

CASE STUDY 10: SOLAR PHOTOVOLTAICS.

SOLAR PHOTOVOLTAICS: MULTIPLE DRIVERS OF TECHNOLOGICAL IMPROVEMENT

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AUTHORS' SUMMARY

A variety of factors, including government activities, have enabled the two orders of magnitude reduction in the cost of solar photovoltaics (PV) over the past five decades. Despite this achievement, the technology remains too expensive compared to existing electricity sources, such that widespread deployment depends on substantial future improvements. No single determinant predominantly explains the improvement to date. Research and development (R&D), economies of scale, learning-by-doing, and knowledge spillovers from other technologies have all played a role in reducing system costs.

Improvements in electrical conversion efficiency have accounted for about one-third of the decline in cost over time. R&D, especially public sector R&D, has been central to this change. Deployment of PV has also benefited from a sequence of niche markets in which users of the technology were less price sensitive and had strong preferences for characteristics such as reliability and performance, which allowed product differentiation.

Governments have played a large role in stimulating increasing demand for PV which has further reduced costs by enabling opportunities for economies of scale in manufacturing. Japan's program was especially innovative in that it not only adopted a long time horizon, but also set a declining subsidy which fell zero after the 10 years of the program. This provided not only a clear signal about market demand, but also clear expectations of future levels of subsidy. The Renewable Energy Law in Germany in the 2000s successfully replicated many of the features of Japan's program.

The current emergence of new technological generations, including thin film and organic PV, will require some reallocation in emphasis from market support to technical support through R&D, recognizing the sequence of innovation efforts from R&D to market formation to local learning-by-doing in the history of the dominant crystallized silicon PV.

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1 INTRODUCTION

A variety of factors, including government activities, have enabled the two orders of magnitude reduction in the cost of PV over the past five decades. Research and development (R&D), economies of scale, learning-by-doing, and knowledge spillovers from other technologies have all played a part in driving technological improvement and reducing PV system costs. Not all of these factors, and the interactions between them, were important for the entire sequence of the technology's development. Certain factors dominated for periods defined by shifts of emphasis in the innovation efforts of both the private sector and governments. From the 1970s to 1985, emphasis was on R&D to improve efficiencies and manufacturing techniques of crystallized silicon PV. In the 1990s and early 2000s, the emphasis shifted to long-term demand programs that enabled economies of scale in manufacturing. And in the 2000s, innovation efforts focused on stimulating local learning-by-doing to reduce installation costs in addition to continuous improvements through manufacturing scale. This sequence from R&D to market formation to local learning-by-doing for the historically dominant crystallized silicon PV may now be repeated for emerging alternative solar technologies including thin film and organic PV.

2 R&D AND EFFICIENCY IMPROVEMENTS

The average electrical conversion efficiency of PV systems has more than doubled since the first commercial systems in the 1970s. Efficiency has been important to cost reductions, accounting for about a third of the decline in cost over time (see Figure 1). R&D, especially public sector R&D, has been central to this change. Data on the highest laboratory cell efficiencies over time show that of the 16 advances in efficiency since 1980 (Surek, 2003) only six were accomplished by firms that manufacture commercial cells. Most of the improvements were accomplished by universities and government laboratories, none of which would have learned from experience with large-scale production; government and university R&D programs produced 10 of the 16 breakthroughs in cell efficiency. Almost every one of the twenty most important improvements in PV occurred during a 10-year period between the mid-1970s and the mid-1980s (Green, 2005), most of them in the US where over a billion dollars were invested in PV R&D during that period (Taylor et al., 2007).

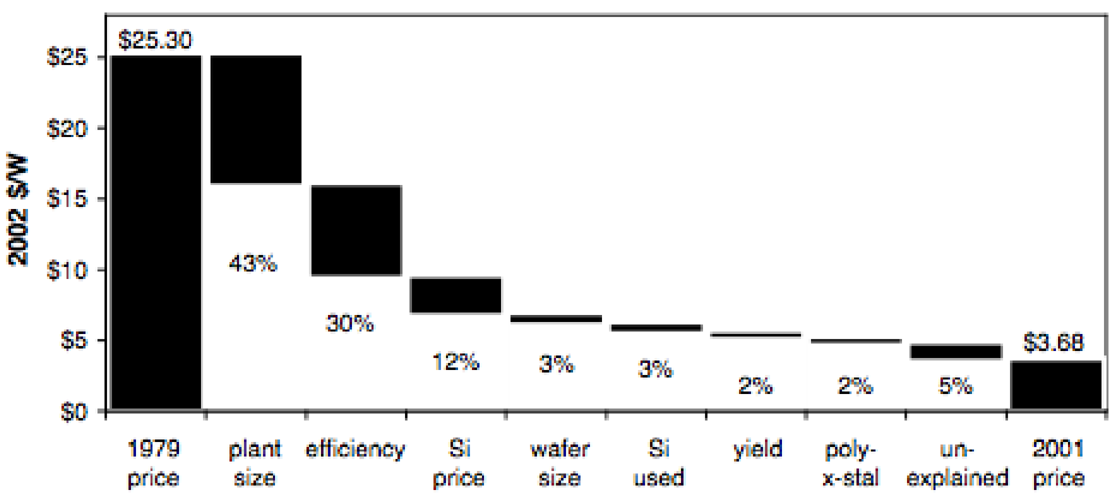

FIGURE 1. PORTION OF COST REDUCTION IN PV MODULES ACCOUNTED FOR BY DIFFERENT FACTORS. NOTES: SI = SILICON. POLY-X-STAL = POLY-CRYSTALLINE.

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As a second perspective on R&D outcomes, Husmann used a combination of expert opinion and patent citations to identify 17 breakthroughs in PV technology from the 1940s through the early 1990s (Husmann, 2011; Nemet and Husmann, 2012). The timing and type of organization creating the breakthrough are shown in Figure 2. Examples of breakthroughs in PV technology include: Boron dopants (1947), anti-reflective coatings (1961), hydrogen passivation (1975), ethylene vinyl acetate (EVA) as a laminating material (1975), and reactive ion etching (1976). The earliest breakthroughs occurred in commercial settings before a substantial PV R&D program began in the mid-1970s, and included inventions by Bell Laboratories, Hoffman Electronics, and Westinghouse Electric. Most breakthroughs, however, occurred during the period of highest R&D from the mid-1970s to the mid-1980s.

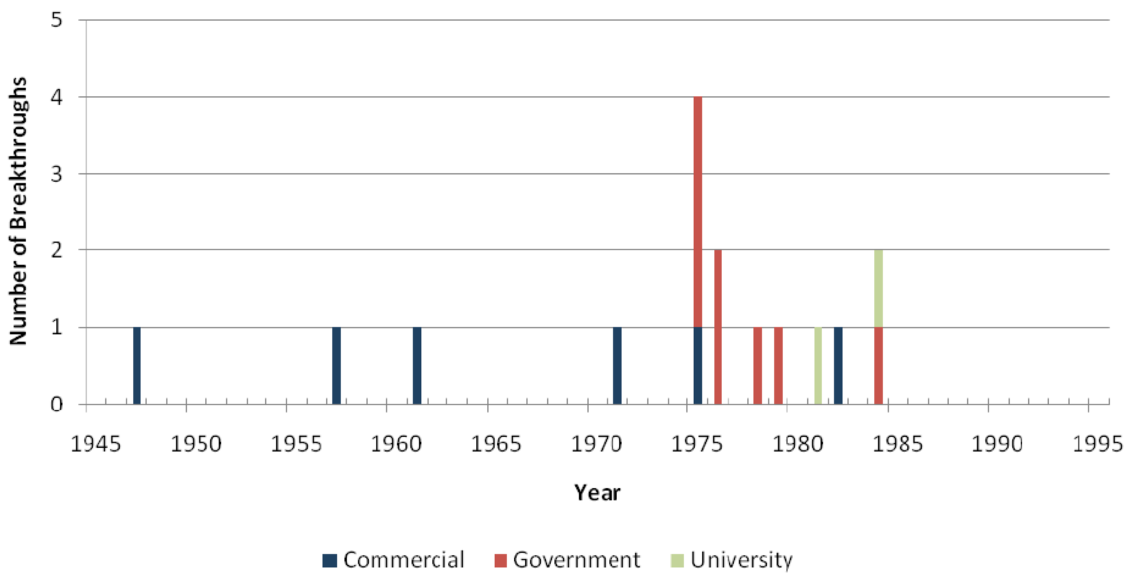

FIGURE 2. FREQUENCY OF BREAKTHROUGHS IN PV TECHNOLOGY BY ORIGIN. SOURCE: HUSMANN, 2011; NEMET AND HUSMANN, 2012.

3 SEQUENTIAL NICHE MARKETS

Deployment of PV has benefitted from a sequence of niche markets. Customers in these markets were less price sensitive and had strong preferences for characteristics such as reliability, grid independence, and performance (including flexibility and weight) that allowed product differentiation. Governments have played a large role in creating or enhancing these niche markets. In the 1960s and 1970s the US space program and the Department of Defense accounted for more than half the global market for PV. The high cost of electricity in space allowed PV to be competitive even at an early stage and even when electricity was above $200/kWh (at least three orders of magnitude above current US wholesale rates). Subsequent niche markets included telecom repeater stations, off-grid homes, and especially consumer electronics such as toys, calculators, and watches. Each was important independently of government decision making and innovation policy. This allowed the PV industry to expand from the mid 1980s until the late 1990s during which time energy prices fell and alternative energy sources lost their importance as a social priority. From the 1990s onwards, households with strong preferences for environmental protection created larger markets, especially as rooftop PV was a conspicuous, socially visible form of pro-environmental action. Figure 3 shows the progression of sequential PV niche markets in Japan. Especially important at early stages were: calculators, consumer electronics, signals, and off-grid applications.

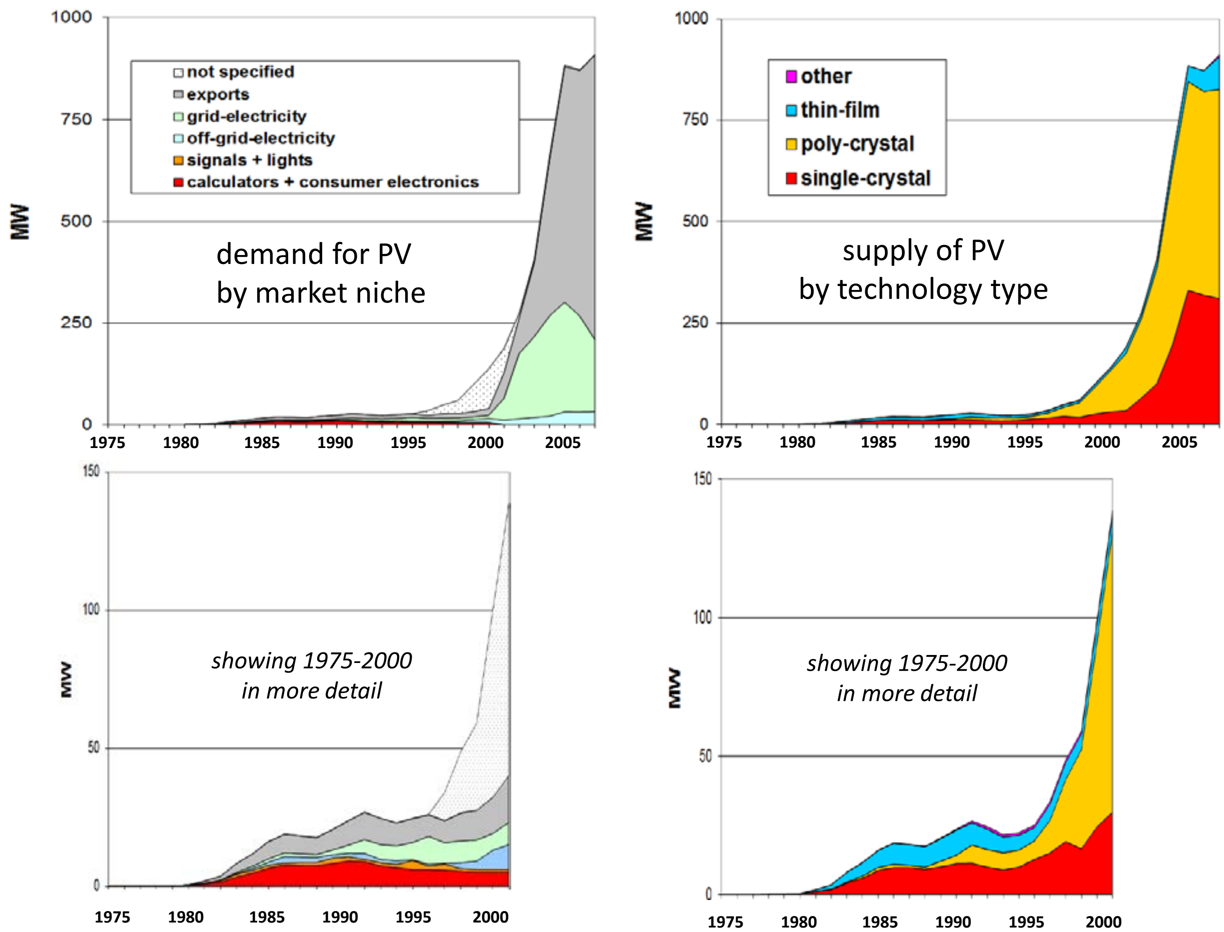

FIGURE 3. CATEGORIES OF DEMAND NICHES AND TECHNOLOGY TYPES FOR PV IN JAPAN. NOTES: LEFT-PANELS SHOW SIZE OF DIFFERENT MARKET NICHES OR DEMAND FOR PV; RIGHT-PANELS SHOW PV TECHNOLOGIES SUPPLYING THIS DEMAND (UNITS SHOWN IN CAPACITY TERMS). TOP-PANELS SHOW FULL TIME SERIES AND Y-AXIS; BOTTOM-PANELS SHOW TRUNCATED TIME SERIES AND Y-AXIS TO EXPAND ON PRE-2000 DATA. SOURCE: WATANABE ET AL., 2002; JPEA, 2010.

4 MARKET DEMAND AND EXPECTATIONS

Increasing demand for PV has reduced costs by enabling opportunities for economies of scale in manufacturing. Nemet (2006) assembled empirical data to populate a simple engineering-based model identifying the most important factors affecting the cost of PV modules over the past three decades. That study found that three factors account for almost all of the observed cost reductions: (1) a two orders of magnitude increase in the size of manufacturing facilities that provided opportunities for economies of scale; (2) a doubling in the electrical conversion efficiency of commercial modules; and (3) a fall in the price of the primary input material, purified silicon. Because investments in larger facilities take time to payoff, economies of scale depend on expectations of future demand. As a result, public programs that reduce uncertainty by setting clear long-term expectations, such as Japan's Sunshine Program in the 1990s (Shum and Watanabe, 2007), are more effective at enabling scale economies than generous subsidies that can suddenly disappear, such as California's incentives for wind and solar in the early 1980s. Japan's program was especially innovative in that it took not only a long time horizon but also set a declining subsidy such that it fell to zero after the ten years of the program (Figure 4). This provided not only expectations of demand but also clear expectations of future levels of subsidy.

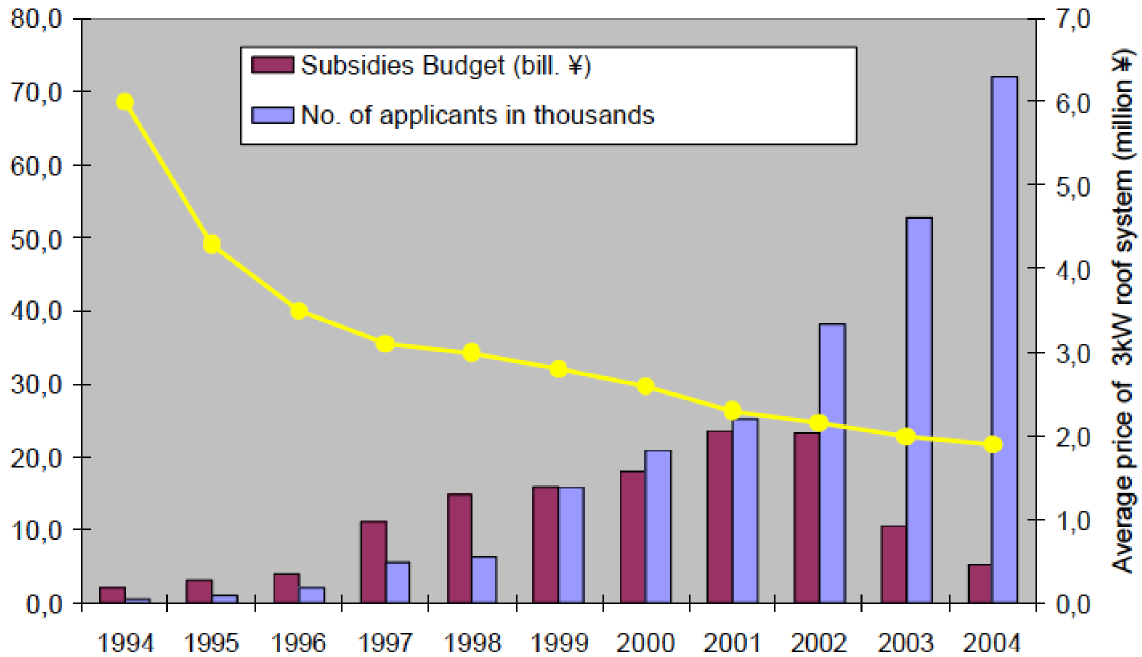

FIGURE 4. JAPAN SUBSIDIES AND APPLICATIONS FOR ROOFTOP PV SYSTEMS. NOTES: BARS SHOW SUBSIDIES AND APPLICATIONS ON LEFT Y-AXIS; LINE SHOWS AVERAGE PRICES ON RIGHT Y-AXIS. SOURCE: JÄGER-WALDAU, 2004.

Government programs with longer time horizons, such as Germany's feed-in-tariffs in the 2000s and the California Solar Initiative launched in 2006, create similar opportunities (Nemet, 2007; Peevey and Malcolm, 2006). Germany's program is especially notable in that production there has become sufficient to create external economies of scale with the emergence of machine tool manufacturers that now produce equipment specifically for the PV industry (Neuhoff et al., 2007). Similarly, production of lower purity, and thus cheaper solar-grade silicon is now profitable because plants can be built at large scales. Economies of scale in unit size are also now observable: large installations show much lower costs per Watt than do small residential systems (Wiser et al., 2009). Increasing installation size is likely to become more important as economies of scale reduce module manufacturing costs, leaving installation costs as an increasingly large share of system costs (with total costs comprising module costs and 'balance of system' costs including hardware, mounting, and installation).

5 LEARNING BY DOING & KNOWLEDGE SPILLOVERS

Learning from experience in production has played a rather small role in reducing module costs (Nemet, 2006). However, learning by doing may play a much more important role in reducing installation costs

(Benthem et al., 2008). An important aspect of this learning is that it is a local phenomenon, whereas module production is truly global (Shum and Watanabe, 2008). As installation costs become a larger portion of total system costs, the extent of this learning by doing will become increasingly important. Whether or not the benefits of this learning are appropriable by private installers will determine whether governments need to play a role in promoting learning investments. For example, there may be benefits to free riding on the experiences of others which may slow down the pace of learning.

Like many technologies, PV has benefitted from the adoption of innovations that originated in other industries. These include: the use of excess purified silicon from the chip-making industry; the use of wire saws from radial tires to slice multiple silicon wafers; electronics connectors to ease installation; screen printing techniques from lithography; as well as an array of manufacturing techniques taken from microprocessors in the case of crystallized silicon PV, and from LCD displays in the case of thin film PV (Keshner and Arya, 2004).

The global aspect of module manufacturing suggests that inter-firm and inter-national technology spillovers are likely to be more important in module production than in installation. International spillovers can be found in trade statistics as knowledge embodied in devices. The distinction between the value of capital and of knowledge in trade data can be difficult to observe directly. Recent efforts have augmented trade data with patent citation data to better identify flows of knowledge from entities in one country to those in another (Dechezleprêtre et al., 2011; Popp et al., 2011).

6 INTERACTIONS BETWEEN R&D AND DEMAND

Certain periods in the history of PV have seen particular drivers of innovation dominate. R&D led to improved efficiencies and manufacturing techniques from the 1970s to 1985. Market formation and demand-side programs underwrote manufacturing economies of scale in the 1990s. And, described further below, local learning-by-doing helped reduce installation costs in the 2000s. But although particular factors dominate in particular periods, interactions among the various factors have also been important. One such “virtuous cycle” was particularly relevant in Japan in the 1990s, when both strong demand-side policies and support for R&D existed simultaneously (Watanabe et al., 2000). In this case, it was not so much efficiency breakthroughs and alternative cell designs that drove improvements, but rather support from the Japanese government via the Ministry of Economy, Trade and Industry (METI) that enabled coordination of expectations and sharing of best practices which in turn supported manufacturing improvements. The influence of the US government may have played a similar role in enabling the 1970s breakthroughs, not just through providing resources for R&D, but by creating a sense of commitment that convinced many to work on the technical and market challenges associated with commercializing this nascent technology (Laird, 2001).

7 COST TRAJECTORIES

Changes in demand and in market structure have affected the cost of PV as well, even if they don’t directly affect the technical characteristics of the technology. Changes in industry concentration in the 1980s and 1990s affected market power and led to a changing relationship between prices and costs over time. The very high levels of demand in the 2005 - 2007 period were in part to blame for the high prices during that period which led to a reversal in the multi-decade downward cost trajectory. This can be clearly seen in Figure 5 which shows the ‘learning curve’ of PV module and system prices as a function of cumulative deployment. A rough estimate suggests that half of the cost increase as cumulative capacity grew from 2 GW to around 10 GW was due to higher material costs and the rest likely due to higher willingness-to-pay, as aggressive subsidy programs brought new consumers to the market for PV. The most recent data from the IPCC's Special Report on Renewable Energy (SSREN), also shown in Figure 5, indicates the downward cost trend for PV modules has resumed.

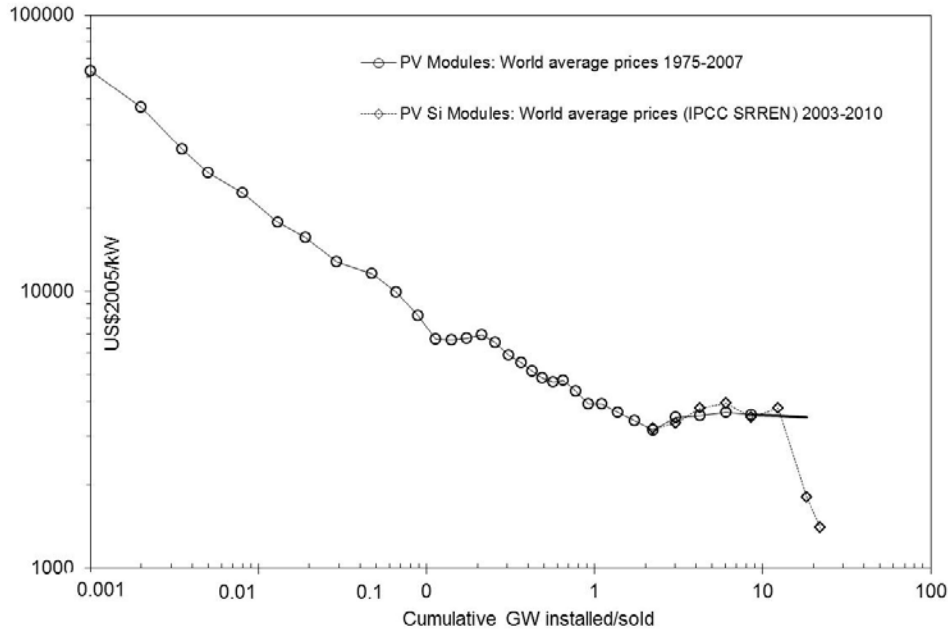

FIGURE 5. PRICES FOR PV MODULES (1975-2010) AND PV SYSTEMS (1998-2009). SOURCES: EDENHOFER ET AL., 2011; NEMET AND BAKER, 2009; WISER ET AL., 2009.

Most cost assessments of PV have focused on the evolution of the core technology, the modules which convert sunlight to electricity. However, modules no longer dominate systems costs. As the prices of modules have fallen, the rest of the components that comprise a PV system have accounted for an increasing share of the overall costs. A study of balance of system ('BOS') prices in the 1990s found that the rate in technology improvement in BOS components has been quite similar to that of modules, which some may find surprising given the heterogeneous set of components and activities that fall under the rubric of BOS (Schaeffer et al., 2004). The dispersion in the data for BOS components is higher than that for modules. The cost of inverters, the largest hardware component of BOS, improved more slowly than modules. However non-inverter costs including installation, wiring, and mounting systems, improved even more quickly.

More recently, work at Lawrence Berkeley National Laboratory has documented the cost of U.S. installed systems from 1998-2010 (Wiser et al., 2009; Barbose et al., 2011). System costs have fallen from over $10,000/kW in 1998 to $6,200/kW in 2010, with an unusually large decline during 2010. Further detail is shown in Figure 6 which includes the number of systems and total capacity installed each year.

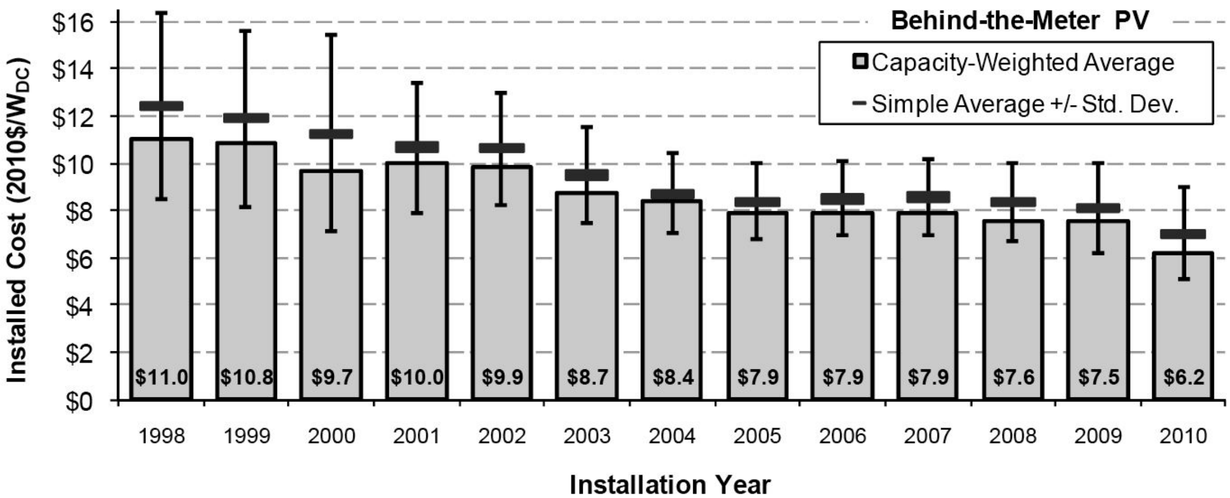

FIGURE 6. INSTALLED COST OF PV SYSTEMS (1998-2007). SOURCE: BARBOSE ET AL., 2011.

8 CONCLUSIONS & PROSPECTS FOR THE NEXT GENERATION OF PV TECHNOLOGIES

The history of PV technology is in many ways a success story when one considers the factor of 100 reduction in costs since the first cells in the 1950s. This story is important not only for its lessons for other technologies, but also for the implications for future developments of PV.

PV has the potential to be very important for climate change mitigation and energy security yet still costs more than conventional power sources. Several observations are prominent from the large set of studies documenting these developments.

- The success of PV is attributable not mainly to one area of emphasis but to a wide array of supporting policy instruments, including: R&D, demand subsidies, industrial development and coordination.
- R&D support needs long-term commitment. A commitment can convey credibility through budget consistency, grants that span multiple years, or supporting policies with their own longevity, such as Japan's Sunshine Program. An alternative means for establishing the credibility of long-term commitments was Nixon's Project Independence in the US which made clear that leadership considered alternative energy a serious national priority.
- A sequence of niche markets with sequentially declining willingness to pay has been essential for the development of the PV industry. Niche markets have been most effective when they were not government supported. For example, remote telecommunications applications, off-grid residences, and consumer electronics helped the industry grow and the technology improve even though government programs did not directly support them. In this sense, PV could be considered fortunate, as natural niche markets in the absence of government support do not exist for all technologies.
- Long-term demand subsidies with clear timelines have been crucial to stimulating deployment and reducing costs because the benefits of demand subsidies come from expectations about markets in

the long-term. Clear expectations encourage private sector investments with long-term payoffs, such as large manufacturing facilities and technology development.

Based on these insights on successful innovation policies, what are the prospects for the new technological generations of PV? Recent work suggests that their success may require renewed R&D support even while markets for the existing technology are expanding (Nemet and Baker, 2009). As with other technologies, the need for R&D investment does not end once commercial markets take off. PV based on crystalline silicon has remained the overwhelmingly dominant technology for three decades despite the advantages of thin film technologies that use less raw material and are more amenable to mass manufacturing techniques. Given that installation methods, inverters, and maintenance are quite similar across types of PV, there is likely more opportunity for inter-generational spillover in system installation than in module production. So an important innovation-related policy question is the extent to which learning and improvement in crystalline silicon PV modules will be transferable to thin film modules.

Innovation policy oriented toward the longer term must address subsequent generations of PV technology, such as those based purely on organic materials. Nemet and Baker 2009 found that production-related effects on technological advance—learning-by-doing and economies of scale—are not as critical to the long-term potential for cost reduction in organic PV than is the investment in and success of R&D. The emergence of new technological generations will require some reallocation in emphasis from market support to technical support through R&D, recognizing the sequence of innovation efforts from R&D to market formation to local learning-by-doing in the history of the dominant crystallized silicon PV.

9 FURTHER READING

The following references give useful additional detail to the innovation history of solar PV: Barbose et al., 2011; Laird, 2001; Nemet and Husmann, 2012; Nemet, 2006.

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