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Experience Curves of Photovoltaic Technology

Harmon, C.

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International Institute for Applied Systems Analysis
Schlossplatz 1 • A-2361 Laxenburg • Austria
Telephone: (+43 2236) 807 342 • Fax: (+43 2236) 71313
E-mail: publications@iiasa.ac.at • Internet: www.iiasa.ac.at

Interim Report **IR-00-014**

Experience Curves of Photovoltaic Technology

Christopher Harmon (christopher_harmon@hotmail.com)

Approved by

Leo Schrattenholzer
Project Leader, Environmentally Compatible Energy Strategies (ECS) Project

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Contents

Abstract

This paper examines the technological evolution, application, and cost trend of photovoltaic (PV) technology over the last three decades. It presents the longest experience curve for PV systems assembled to date; stretching back to the pre-commercialization period in the late 1960s. Cooperative investments by manufacturers and individual governments have resulted in the accumulation of experience within the solar industry and the subsequent cost reduction of PV systems. Significant cost reductions have occurred in both PV modules, that house the solar cells, and the ancillary components, know as balance-of-system (BOS). Between 1968 and 1998, the worldwide cumulative installed capacity of PV modules doubled more than thirteen times, from 95 kW to 950 MW, while costs ($\$/W_p$) were reduced by an average of 20.2% for each doubling. Cost reductions for PV modules are attributed to technology innovation, manufacturing improvements, and economies of scale. Though BOS are difficult to compare to one another—due to the customization of PV applications—targeted studies have shown that BOS costs have fallen over the past two decades and in some instances, more than module costs. BOS cost reductions are attributed to greater system integration and the experience of system designers and installers. Future cost improvements will be attained through greater standardization and pre-assembly of BOS components in the factory.

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About the Author

Christopher Harmon is a 1998/99 U.S. Fulbright Fellow in the Department of Energy and Environmental Studies at Lund University, Sweden.

Experience Curves of Photovoltaic Technology

Christopher Harmon

1 Introduction

The stimulus for the development of non-fossil fuel based energy alternatives has changed somewhat over the last three decades. While the horizon for the depletion of fossil fuel resources is now placed well into the next century, global warming—primarily as the result from energy generation—poses a much more eminent threat. Subsequent energy policies have sought to invest in alternative technologies that decrease pollutant emissions and therefore mitigate global climate change.

The breadth of energy alternatives—fossil fuels, nuclear and renewables—that will be available to us in the future is largely built upon choices and investments made today. Technology development is a dynamic process, in which the adoption and diffusion of a technology can take decades. The level of investments for research, development and demonstration (RD&D) determines the pace of diffusion. With continued investment, a technology gains experience in the marketplace, resulting in cost reductions and increased economic competitiveness. If technologies utilizing renewable fuels are to be available to us in the future, then early and continuous investments are essential.

It is vital to chart the cost evolution of a technology so that policy-makers are better able to assign appropriate RD&D funding for energy technologies. An "experience curve" is one valuable tool used to illustrate a technology's historic cost trend and forecast its future projection. Experience curves express the correlation of unit cost reductions with increasing cumulative installations. This paper is an in-depth examination into the experience curve of a leading non-fossil fuel technology: photovoltaics.

The term "photovoltaic" refers to a family of technologies that convert light directly into electricity. Photovoltaic technology (PV) is an appealing alternative to fossil fuel-based power generation because it is a renewable, environmentally benign, and domestically secure energy source. Moreover, PV technology is modular and can be readily scaled to meet demand. PV systems range in size from several kilowatt residential systems to utility-scale multi-megawatt applications. However, widespread adoption of photovoltaic technology outside several niche markets is currently bounded by its relatively high cost as compared with traditional fossil fuel technologies.

This paper intends to provide a succinct definition of current photovoltaic technology and accurately unify efficiency, shipment, cost and pricing data. To begin, a basic description of PV technology and PV system sub-components is given in Section 2.

This section also differentiates between the predominant categories of PV modules—presenting their construction attributes, efficiencies and market share. Section 3 identifies which applications are attractive for "on-grid" and "stand-alone" PV systems. Section 4 goes further to characterize the historic market growth of PV technology and the patterns of global production and installation. Importantly, Section 4 presents cumulative PV module shipments from 1976, the year PV technology was commercialized, through 1998. Cumulative shipment data provides one of two essential parameters in constructing the experience curve of PV systems. The second parameter, cost data, is detailed in Section 5. Section 6 then synthesizes the cost and shipment data from the prior sections along with pre-commercialization data into experience curve spanning from 1968 to 1998. This experience curve is the longest and most comprehensive learning curve amassed for photovoltaic technology. The quantitative and qualitative findings are intended to aid in the understanding the evolution of photovoltaic technology in order to better assess its future diffusion potential into our global energy system.

2 Description of PV Systems

Photovoltaic (PV) technologies, also commonly known as "solar cells", are solid-state semiconductors. PV systems consist of two major subsystems of hardware: PV modules and the Balance-of-System (BOS). PV modules house an array of solar cells that deliver direct current (dc) power, whereas BOS equipment include components needed for mounting, power storage, power conditioning and site-specific installation.

2.1 PV Technology

The basic element of photovoltaic technology is the solar cell (typically 10 cm x 10 cm square). Solar cells are constructed by joining two dissimilar layers of semiconducting materials, referred to as p-type (positive) and n-type (negative) semiconductors. "Doping" a semiconductor, usually crystalline silicon, with an impurity (typically boron) creates a deficit of negatively charged electrons, producing a "p-type" semiconductor. Similarly, n-type semiconductors are doped with small impurities, typically phosphorous, that result in a surplus of free electrons. A solar cell is constructed by joining these two semiconductors in a "p-n junction", producing an electric field. The photovoltaic effect is enacted when sunlight, comprised of positively charged photons, is absorbed by the solar cell, transferring energy to the electrons that then become part of a current in an electrical circuit. In addition to the semiconductors, a solar cell consists of a transparent encapsulant (typically glass) to prevent weathering, an anti-reflective layer, and a contact surface to transfer the electric current to the load.

2.1.1 PV Modules

A PV module is an array of packaged solar cells that convert solar energy directly into direct-current (dc) electricity. Individual PV module outputs range between 10 W_p (peak Watts) to 300 W_p (each cell, measuring approximately 10 cm x 10cm, generating 1W_p), but scaling allows PV modules to be linked into panels and further, panels into arrays to meet the desired electrical load (NREL, 1998).

Virtually all of the installed PV systems in the world are “flat-plate” systems that use large areas of semiconductors to convert direct and diffuse solar radiation. While some flat-plate systems are made to rotate to track the sun, most are fixed and have no moving parts. Alternatively, PV systems known as “concentrators”, utilize optic lenses to focus direct sunlight onto comparatively smaller areas, thereby reducing the amount of necessary semiconducting material.

2.1.1.1 Crystalline Silicon PV

Silicon is the most common semiconducting material in use in PV modules due to its abundance. Single-crystal silicon, or monocrystalline silicon, semiconductors are the most efficient in transferring electrons due to their uniform structure, but are also the most expensive. Excluding the market for indoor-consumer-equipment with low power requirements, for example a calculator, monocrystalline silicon modules accounted for 48.4 MW_p, or 60% of the 82.4 MW_p global PV market in 1996. A newer variation of the monocrystalline cell are silicon “ribbon” cells which are formed by cutting ribbons from a thin monocrystalline sheets. While silicon ribbon cells hold promise of future manufacturing cost reductions, they constituted just 3% or 3 MW_p of the global market in 1996 (EIA, 1998). Crystalline silicon PV cells have figured prominently in the commercial marketplace because of their durability and efficiency performance. Today, modules constructed of monocrystalline silicon, yield efficiencies of 12% in the field (Thomas, 1999). In laboratory environments, module of crystalline silicon cells achieved efficiencies of 22.7% in 1998, up from 7% in 1976 (Green, 1998). Factors such as dust and encapsulants reduce the light reaching the solar cells in the field and thus limit the efficiency.

The next most prevalent type of semiconductor is cast “multi-crystal” or polycrystalline silicon, accounting for 24 MW, or roughly 30% of the PV modules shipped in 1996 (Little, 1997; EIA, 1998). Polycrystalline silicon is less expensive to manufacture than monocrystalline silicon, however, it is less efficient in transmitting electrons due to the existence of grain boundaries. Polycrystalline silicon modules exhibit 9% efficiencies in the field (Kelly, 1993).

2.1.1.2 Thin-film PV

An emerging alternative to crystalline silicon is thin-film PV. Thin-film, flat-plate systems use 1/20 to 1/100 of the material needed for crystalline silicon semiconductors by employing a film of semiconducting material only 1 micron (10^{-6} meters) thick. The most prominent type of thin-film photovoltaic in production, amorphous silicon (a-Si), accounted for 5.9 MW or 7% of the outdoor PV market in 1996. Two other thin-film photovoltaics under development that demonstrate potential for large-scale PV module manufacture are cadmium telluride (CdTe) and copper indium diselenide (CIS), though they held less than 1% of the PV market in 1996 (Little, 1997).

Lower material volumes for thin-film PV, as compared with crystalline silicon, result in lower material costs. In principle, thin-film PV cells also exhibit a greater propensity for mass-manufacturing cost reductions as compared with crystalline silicon (NREL, 1997; Williams 1993). However, commercially available thin-film PV have not attained field efficiencies greater than 6%, as compared with the 12% efficiency of crystalline silicon PV modules (Thomas, 1999). Though laboratory tests have yielded promising thin-film efficiencies, manufacturers have not yet translated the high-efficiencies and high-yields of smaller, laboratory-constructed thin-films up to production volumes (Gay, 1997).

The economic competitiveness of a PV module is measured in dollars per peak watt ($\$/W_p$) and is therefore impacted by both unit cost and efficiency. The challenge for thin-film PV manufacturers is to consistently produce cells at commercial-scale geometries and volumes with efficiencies akin to crystalline silicon cells, if they are to capture more of the photovoltaic market.

2.1.2 Balance-of-System (BOS)

Ancillary equipment, referred to as the balance-of-system (BOS), is necessary to install and deliver electricity from a PV module. BOS requirements vary between applications due to site-specific power and reliability requirements, environmental conditions, and power storage needs. BOS components include mounting equipment such as frames and ballasts to support and elevate the PV module/panel. A small portion of installed PV systems also use tracking systems to follow the sun, thereby increasing the exposure to incident sunlight. Power conditioning equipment limits current and voltage, maximizes power output, and converts direct-current (dc) electricity generated by the PV array into alternating current (ac) electricity through a dc/ac inverter. Power storage is a desirable—or in many instances a compulsory—power system requirement, and thus a battery and a “charge controller” device must be added to the BOS. PV systems necessitate protective electrical hardware such as diodes, fuses, circuit breakers, safety switches and grounds, as well as wiring to connect the PV module and BOS components. (Notton, 1998; Stern, 1997; NREL, 1999).

In applications where a PV system will be supplementing a “base load” or where power *must* always be available (i.e. nights or cloudy days), a PV system is usually integrated with an auxiliary electric generator. This hybrid system does not necessarily fall under the definition of BOS, but an additional electric generator will impact the overall sizing of the PV system, the battery and other BOS components.

3 PV Applications

Solar cells are ideal energy candidates in niche markets where: (1) electric-grid extensions are not economical, (2) peak electrical demand is coincident with maximum solar intensity (e.g. cooling loads), or (3) where the attributes of PV technology as a clean and modular power source are valued at a premium.

The PV market can be grouped into grid-connected and “stand-alone” applications. Grid-connected applications—accounting for approximately 20-30% of worldwide PV installations—include central PV stations or distributed, small-scale PV systems sited near consumers. Stand-alone PV applications are the most prevalent, constituting 60-70% of PV installations. Some common examples of stand-alone PV system applications include roof-top residential/commercial systems, remote water pumping stations, telecommunications equipment, and individually powered appliances or lights (Siemens, 1998).

4 PV Market Growth

Photovoltaic technology was initially developed during the late 1950s to provide long-term reliable power for satellites. Companies began to offer PV technology for commercial application in the mid-1970s. After the nascent years of the industry, the PV market has demonstrated a consistent average annual growth of 15-16% since 1983, when the cumulative installed base was 15 MW_p (Williams, 1993; Thomas, 1999). Figure 4-1 illustrates the cumulative shipment of PV modules that has grown from less than a megawatt in 1976 to 941 MW_p in 1998.

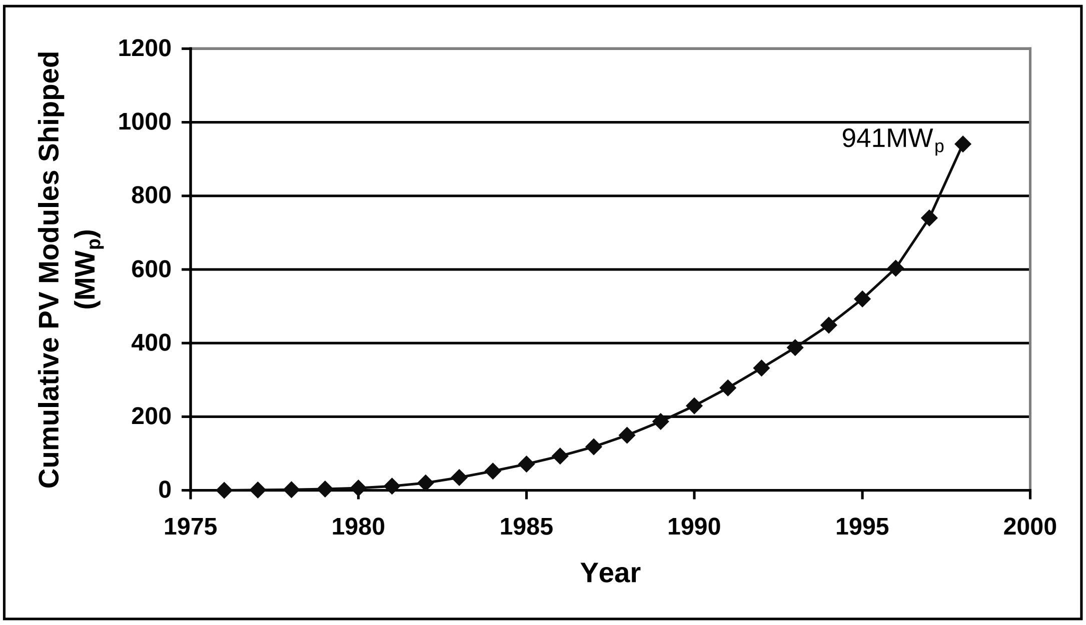

Figure 4-1: Cumulative worldwide PV module shipments [1976-1998] (Ayres, 1998, NREL, 1999)

The market for PV technology in the long-term future is uncertain, though it is reasonable to presume that it will not diverge radically from its past annual growth rate of 15% in the next decade. PV system costs continue to decline and there is an ever-expanding global market for generating capacity. In 1995, the 579 MW cumulative installed capacity of PV technology represented just 0.02% of the global power generating capacity of 3,079 GW. By 2020, the International Energy Agency projects that global power demand will be in the neighborhood of 5,900 GW (IEA, 1998). To capture these opportunities, continued public and private investment into PV system RD&D will be required.

PV manufacture is a high-technology industry, centered in the United States, Japan and Europe. In 1995, PV production in the United States amounted to 44% of the 78 MW_p annual global photovoltaic market, while Japanese and European manufacturers held 17% and 21%, respectively (Watanabe, 1999; EIA 1998). Though, relative shares between these regions do fluctuate annually. To illustrate, the United States' market segment declined to 38% of the 150 MW_p annual global PV market in 1998, while the Japanese and European shares increased (NREL, 1999). Other notable, though currently less significant areas of PV manufacture include Australia and India.

Export of PV modules accounted for over 70% of PV shipments in the United States in 1997. Two countries outside the United States accounted for 39% of total shipments: Japan (8,056 kW_p) and Germany (11,162 kW_p). However, developing nations represent an important expanding market, where PV systems are cost competitive alternatives to electric grid extensions. In 1997, the developing world received 22% (10,794 kW_p) of PV modules exported from the United States (EIA, 1999; Gay, 1997). This export market for PV technology is anticipated to continue to grow due to increasing electricity demand in developing nations.

5 PV System Costs

The cost of a PV module is measured in dollars-per-peak-watt ($\$/W_p$), where "peak watt" is defined as the power of full sunlight at sea level on a clear day. Modules are rated using standard test conditions of 1000 W/m^2, an air mass of 1.5 at 25°C. Thus PV module "cost reductions" are the result of either a decrease in manufacturing cost or an improvement in module efficiency. Figure 5-1 illustrates that since the start of commercial manufacture of solar cells in 1976, crystalline silicon PV module prices have decreased from $\$51/W_p$ to approximately $\$3.50/W_p$ in 1998 (Ayres, 1998; Thomas, 1999). Prior to commercialization, in 1968, laboratory-based PV modules cost approximately $\$90/W_p$ (Maycock and Wakefield, 1975). In a current high-volume module production plant (1.5-2 MW_p/year) single crystalline silicon module costs are divided between silicon wafer manufacture (silicon material costs, crystal growth, and slicing) at 60%, cell fabrication at 15%, and module fabrication at 25% (Ghannam, 1997). An emergent subclass of solar cells, known as silicon "ribbon" cells, show promise of reducing processing costs by cutting ribbons from a thin monocrystalline sheet, thus avoiding the slicing step required of conventional cylindrical ingots (NREL, 1999).

Photovoltaic system costs encompass both module and BOS costs. Indeed, module costs typically constitute only 40-60% of total PV system costs. The module's share of total system costs is largely influenced by the necessity of a battery, that commonly represents half of all BOS costs, and an ac/dc inverter (Ghosh, 1999). It is difficult to quantify "typical" BOS cost contributions as system requirements can vary significantly for each application. Of note: total system installed costs can also vary significantly, possibly including costs for site preparation, laying a foundation, system design and engineering, permitting, as well as assembly and installation labor.

A 1996 cost-survey of PV installations in Western Europe, North America and Japan highlighted the broad variance of installed costs, ranging from approximately $\$14/W_p$ to $\$27.60/W_p$ for "off-grid" PV systems between 100-500 peak watts. Costs for 1-4 kW_p off-grid systems spanned between $\$10/W_p$ to $\$15/W_p$. Notably, these system costs have occurred in developed countries that have established distribution chains as well as experienced PV system designers and installers. Worldwide, installation cost for off-grid systems reach $\$30$–$\$40/W_p$. Similarly, "on-grid" applications also demonstrated cost variations, sometimes up to a factor of three. Of the systems surveyed in 1996, on-grid systems in the range of 1-4 kW_p cost between $7/$W_p$ and $15/$W_p$. Larger on-grid systems, between 10 and 50 kW_p cost $7.50/$W_p$ to $20/$W_p$, while systems larger than 50 W_p did not exceed $13.70/$W_p$ (Bates, 1997). It can be inferred from this data that while module costs are uniform, total PV system costs differ, dependent upon BOS requirements and the experience of the PV industry of a given region.

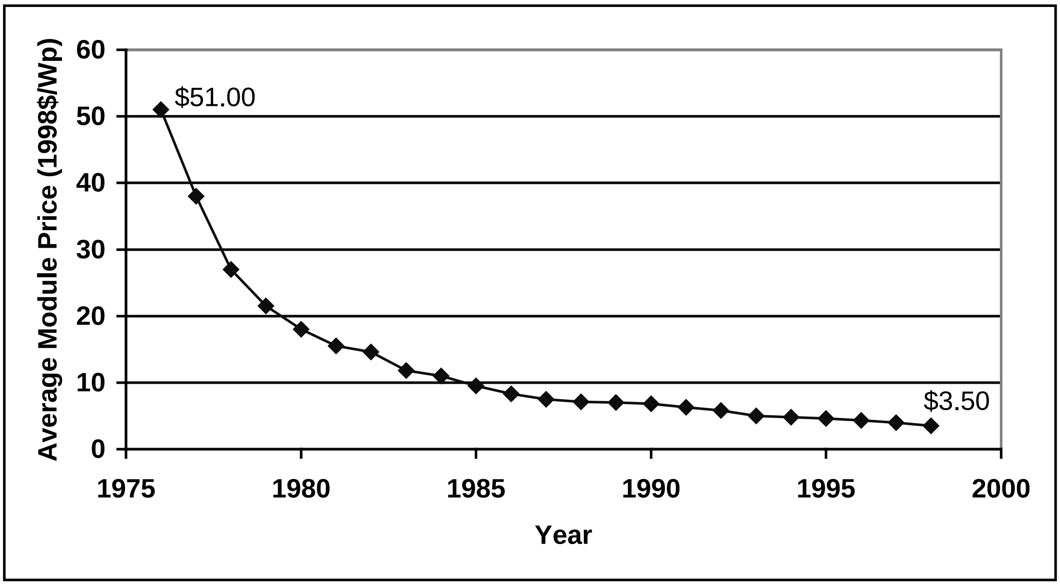

Figure 5-1: The average selling price of PV modules [1976-1998] (Ayres, 1998; Thomas, 1999)

The life cycle cost (LCC) of a PV system may also include costs for site preparation, permits, system design and engineering, installation labor and O & M. Photovoltaic systems have an anticipated 30-year lifetime, though current terrestrial photovoltaic systems have only been in operation for twenty years, since the late 1970s. O & M costs for *modules* are nominal, ranging between 0.02 to 0.1 cents/kWh (Neij, 1997). However, documented O & M costs for entire PV systems vary significantly, ranging between as low as $0.01/kWh to $0.10/kWh. The higher reported costs included maintenance costs for generators in remote hybrid PV systems, as well as capital replacement costs due to environmental factors such as extreme temperatures and vandalism. "Typical" maintenance costs lie at the lower end of this range, owing largely to the need for replacement of some of the BOS components (Thomas, 1999). The most significant replacement cost will likely be the battery—lasting between five and nine years, depending on use (Rosenthal, 1998; Notton, 1998, Zweibel, 1990). Though not all researchers agree whether O & M costs can be strictly correlated to system size, one survey of ten PV installations concluded that O & M costs were approximately 2% of total hardware costs (Notton, 1998).

6 Cost Reduction of PV Systems

In keeping with the distinction between PV subsystems made earlier in this paper, this section describes the cost reductions of modules and BOS separately. Module costs are described using a tool known as the "experience curve" that relates historical cost changes as a function of cumulative shipments. In this section, the experience curve is defined and then constructed using module shipment data (found in Section 4) and price data (found in Section 5). Given the lack of continuous and comparable BOS cost data, experience curves cannot be similarly employed, though there is compelling evidence that BOS learning is a leading factor in the historical reduction of PV system costs. Alternatively, BOS cost trends are investigated using several documented case studies.

6.1 Experience Curves

An experience curve is a tool used to describe past—and project future—cost trends. Experience curves are based upon a phenomena observed within many industries that production costs decline with increased experience of production. Moreover, it has been found that unit costs often decline at an invariable rate correlated to cumulative production. This phenomenon is also commonly referred to as "learning" or "learning-by-doing".

Experience curves, depicting historical and unvarying unit cost reductions, have been extrapolated to consider future technology costs. While the use of experience curves should not be seen as a deterministic theory of technological learning, the phenomena has been observed across many technologies (for a discussion and survey see Argote and Epple, 1990) and can provide insight into future cost trajectories.

6.1.1 Definition of the Experience Curve

The experience curve describes how unit costs decline with cumulative production. The curve is generally expressed as:

$$\mathrm{Cost(CUM)} = \mathrm{Cost_o} * \mathrm{CUM}^b \qquad (eq.\ 1)$$

In equation 1, *Cost(CUM)* is the unit cost as a function of output, $Cost_o$ is the cost of the first unit produced, *CUM* is the cumulative unit production over time, and *b* is the experience index. The experience index can be used to calculate the useful concept of the "learning rate". The learning rate is defined as the cost reduction each time the cumulative experience is doubled. The learning rate (*LR*) is expressed below.

$$LR = 1 - 2^b \qquad (eq.\ 2)$$

For example, a technology having a learning rate of 30% has undergone a 30% decrease for each cumulative doubling of production. The causes of cost reduction are attributed to a combination of production improvements (process innovations, learning effects and scaling efforts), product development (product innovation, product redesign, and product standardization) and decreases in process input costs (parts and materials) (Neij, 1999). The experience curve is an aggregate representation of the learning mechanisms mentioned above. It has been argued that scaling factors are separate from the experience effect, but in this paper scaling effects are considered part of experience.

6.2 Development of PV Systems

PV systems are not yet cost competitive with fossil fuel-based generators. A majority of the systems to date have been installed in niche applications (see Section 3) with the help of subsidies or government purchasing programs. However, the combination of government and private investment has spurred learning effects in both module and BOS costs, bringing total PV system costs down.

6.2.1 PV Module Cost Reductions

Although consistent manufacturing *cost* data have not been available, historical PV module *price* data are well documented. In the years before the commercialization of PV technology, Maycock and Wakefield documented module costs of approximately \$90/W_p in 1968 reduced to \$70/W_p in 1974, or a learning rate of roughly 20% (Maycock and Wakefield, 1975). Since the commercialization of PV technology in the mid-1970s, module prices have closely followed this experience curve with a well-defined learning rate. Figure 6-1 is a log-log plot depicting the average price of PV modules as a function of cumulative installed capacity between 1968 (\$90/W_p) and 1998 (\$3.50/W_p). At the outset of commercialization in 1976, module costs were \$51/W_p (Maycock and Wakefield, 1975; Ayres, 1998; Thomas, 1999). The resultant overall learning rate for PV modules between 1968 and 1998 is 20.2%. Findings by Williams and Terzian also confirmed that the PV module selling price on the global market followed an 18.4% learning rate between 1976 and 1992 (Williams and Terzian, 1993). A similar learning rate has been shown at a national level, including Watanabe's documentation of a 20% learning rate for PV modules prices in Japan between 1981 and 1995 (Watanabe, 1999). All of the aforementioned experience curves are aggregated for all types of flat-plate PV modules, consequently neither the disparity in cost, nor learning rate between crystalline silicon and thin-film PV modules can be discerned.

The invariance of the experience curve for PV modules over a 30-year period and more than thirteen doublings, is a reasonable basis for expectation that with continued investment, similar learning is likely in the future. Furthermore, there are two principal reasons for being optimistic about further price reductions of flat-plate systems. First, efficiencies demonstrated in the laboratory continue to climb (see Section 2.1.1.1 and Section 2.1.1.2 for discussion), followed, albeit at a slower rate, by efficiencies in the field. Secondly, most flat-plate PV systems are produced using labor-intensive, batch manufacturing systems, while mass-production and economies-of-scale experienced with larger output volumes will tend to decrease costs (Kelly, 1993). Japanese manufacturers have attributed past module cost reductions to two causes: (1) the accumulation of technology knowledge and (2) economies of scale achieved during production expansion (Watanabe, 1999). Similarly, manufacturers in the United States credit cost reductions to the development of low-cost, high-throughput and high-yield manufacturing processes that have concurrently achieved modest gains in large-area module efficiencies (Ghannam, 1997).

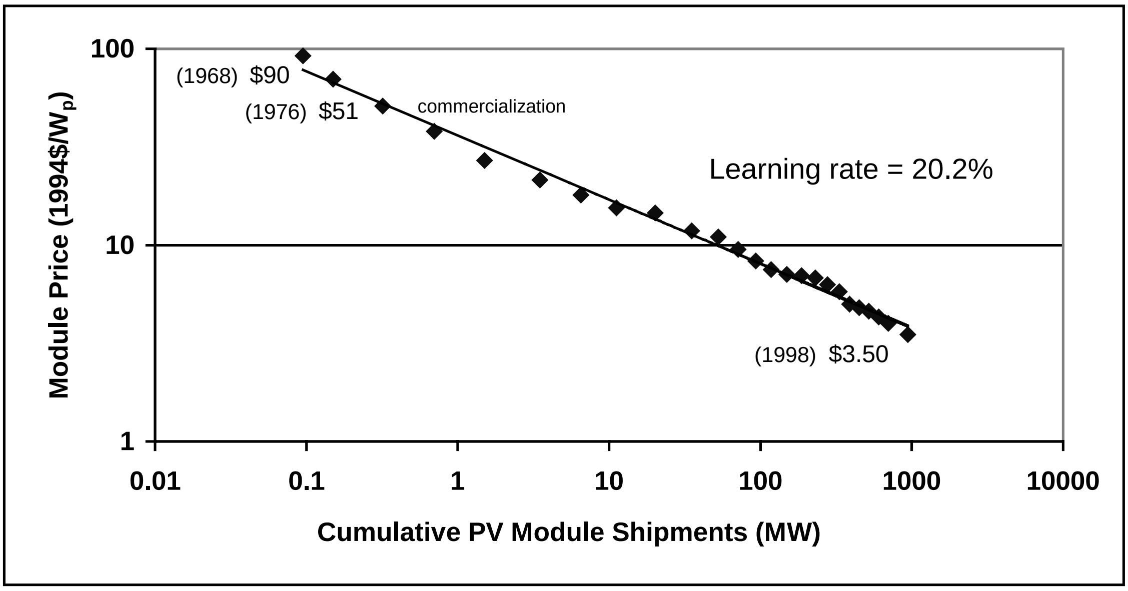

Figure 6-1: The experience curve of PV modules [1968-1998] (Maycock and Wakefileld, 1975; Ayres, 1998; NREL 1999;Thomas, 1999; Watanabe, 1999)

6.2.1.1 PV Module Investment

In recognition of the learning effect, Japan and the United States have both initiated government-sponsored public/private consortiums to cultivate PV system cost reductions. Under the guidance of Japan's Ministry of International Trade and Industry (MITI), the Sunshine Project has provided roughly 60% of the 7.97 billion USD budget between 1981 and 1995 to the eight leading Japanese PV manufacturing firms (Watanabe, 1999). Between 1992 and 1998, the U.S. government shared 58% of 1.14 billion US$ expenditures with domestic PV manufacturers participating in the U.S. Photovoltaic Manufacturing Technology (PVMaT). Specific examples of the on-going research efforts under the 1998 U.S. PVMaT program include:

- development of large-area thin-film solar cells,
- designing a high-volume PV manufacturing line,
- efficiency and throughput advances in continuous roll-to-roll amorphous silicon alloy PV manufacturing technology,
- advances in continuous, automated manufacturing of string-ribbon silicon modules, and
- post-lamination manufacturing process automation for PV modules (Witt, 1998).

6.2.2 BOS Cost Reductions

Though the majority of research concerning the experience of solar cells has been focused on module manufacture, BOS learning has been a significant contributor to the historical reduction of PV system costs.

As compared with PV module price data, there are fewer sources for historical field data on BOS installed costs. Obtaining and amalgamating BOS costs presents many challenges. Foremost, PV applications are inherently one-of-a-kind, each having different electrical and hardware, e.g. BOS, requirements. Moreover, BOS costs, measured in $\$/W_p$, can be subject to scaling factors. To illustrate, PV system costs in 1996 for stand-alone applications, ranging in size from 100W to 4kW, (as discussed in Section 5) spanned between $\$10/W_p$ to $\$28/W_p$ – a difference of a factor of three (Bates, 1997). These joint factors do not lend BOS costs to be dissected by use of an experience curve.

However, there is significant evidence that BOS learning has occurred over the last two decades. Thomas reports that in the early 1980s, the first focused attempt in the United States to utilize the best-available modules and BOS-components resulted in the installation of nearly 350 kW of flat-plate, grid-tied (no battery) photovoltaic systems. Both roof- and ground-mounted systems were installed at an average price of $\$30.00/W_p$ in real 1980 dollars, divided between $\$10.00/W_p$ for the modules and $\$20.00/W_p$ for BOS costs (including site preparation, foundations, structures, wiring and system protection, inverters and engineering). In comparison, a similar grid-tied system in 1998 cost roughly $\$6/W_p$ in real 1998 dollars ($2.96 in 1980 dollars)—module costs accounted for $\$3.50/W_p$ ($\$1.73/W_p$ in 1980 dollars) and BOS costs amounted to $2.50 ($\$1.23/W_p$ in 1980 dollars). While these two systems are not strictly identical, the cost data indicates that BOS costs have fallen along with, if not faster than, module costs (Burgess, 1982; Thomas, 1999).

Unlike PV module learning, BOS learning has not been attributed to cost reductions of individual hardware components. BOS equipment for stand-alone PV systems is comprised of common mass-produced electrical components, with mature markets outside the solar industry. Consequentially, a majority of BOS components have not individually experienced any significant cost reductions. This flat cost trend does not necessarily preclude future price cuts, rather, it implies that cost reductions would only be the result of discrete technological innovation. For example, research has focused on the development of micro-inverters as a cost-effective replacement for traditional inverters (Ghosh, 1999).

In the past, PV systems have been assembled in the field (versus the factory) from materials and hardware characterized by sub-optimal integration, originating from various manufacturers and vendors. Hence, total installed system costs vary, dependent upon the experience of the individual system designer and installer. However, taken as a whole, the solar industry has gained experience, enabling BOS cost reduction via mechanical and electrical integration of PV modules, array structure, and power conversion electronics. Moreover, cost savings have been achieved by reducing the number of individual BOS parts through design efforts. There are on-going efforts to standardize BOS equipment and shift assembly from the field to the factory wherever possible, in order to realize greater cost savings. One study, sponsored by the U.S. Photovoltaic Manufacturing Technology (PVMaT) Project, sought to reduce the installed cost of a 100kW grid-tied, tracking PV array, specifically focusing on improvements in BOS-related assembly. The effort resulted in a reduction in the number of major “field tasks” from 36 tasks to 19 tasks and a decrease in BOS area- and power-related costs of 43% and 51%, respectively. Consequently, the net PV system cost was reduced by 18.3% (Stern, 1997).

6.2.2.1 BOS Investment

Significant attention has been placed on balance-of-system integration improvements for photovoltaic applications as evidenced by the product development efforts sponsored by the U.S. Photovoltaic Manufacturing Technology (PVMaT) Project (see Section 6.2.1.1). Specific on-going manufacturing tasks include the development of:

- an alternating-current 260-300W photovoltaic module (equipped with an integrated micro-inverter, thus eliminating the need for dc wiring and a dc/ac in-home inverter),
- a pre-assembled utility interconnection,
- an integrated power-processing unit (IPPU),
- a low-cost, three-phase digital-control inverter, and
- a standard, pre-wired 240-300W polycrystalline modular unit (equipped with an integrated, digitally-controlled micro-inverter).

The advantages of these products are stated as shorter production lead times, improved quality, increased system reliability, lowered overhead, and reduced material and labor costs (Bower, 1997).

7 Discussion

The primary motivation of this paper is to present the most comprehensive experience curve for PV systems, spanning from pre-commercialization times to the present. Beyond the intrinsic value of experience curves to policy makers, they are instrumental as a mechanism to incorporate technological change into energy systems models. The concept of technological learning recognizes that investments in a technology increase industry experience and result in performance improvements and cost reductions. Experience curves are a tool that allows one to endogenize these technology dynamics into "bottom-up" energy system models. These models, in turn offer critical policy insight into the economic and environmental impacts of energy generation.

In order to effectively examine the technological learning of PV systems it is useful differentiate between PV module learning and BOS learning. PV modules conveniently lend themselves to be described using an experience curve. Between 1968 and 1998, PV module costs declined by an average rate of 20.2% each time the total cumulative installed capacity doubled (for a total of greater than thirteen doublings). This relatively unwavering learning rate—coupled with steady market growth forecasts in the mid-term future and industry predictions for manufacturing improvements—is a strong indicator that future PV module cost reductions are achievable with continued investment. PV module learning is attributed to increases in module efficiencies, manufacturing experience, and economies of scale. It is important to bear in mind that module costs typically represent 40-60% of an installed PV system; BOS costs represent the remainder.

BOS costs have also fallen in unison with module costs during the last two decades. However, due to the inherent uniqueness of PV system applications, experience curves may not be an appropriate tool to describe BOS costs. While individual BOS components have experienced little cost reduction between 1976 and 1998, the cumulative experience of the PV system designers and installers has resulted in learning, i.e. cost reductions, equal to or even greater than that of modules. Cost reductions have been attained through greater system integration and a reduction in the number BOS parts. As signaled by on-going research initiatives, one strategic opportunity for further reducing BOS costs is standardizing BOS to the greatest degree possible and efficiently packaging components so that on-site integration and installation in minimized.

8 Conclusion

The two main sub-systems of PV technology, modules and Balance-of-System (BOS), have benefited from the investment and experience of the solar industry over the last three decades. Between 1968 and 1998, the cumulative installed capacity of PV modules has doubled more than thirteen times, from 95 kW to 950 MW, while module costs were reduced by an average of 20.2% (from \$90/W_p to \$3.50/W_p in 1994 US dollars) for each doubling. Though crystalline silicon modules have dominated the worldwide market for two decades, polycrystalline thin-film photovoltaics can be cheaper to manufacture and show promise of attaining greater efficiencies. Both crystalline silicon and thin-film photovoltaic modules have experienced “technological learning”, stemming from improved cell efficiencies, manufacturing experience, and economies-of-scale.

Although BOS learning has been less homogeneous across the industry, due to the customization needed for each application, the growth of the market has created more experienced system designers and installers. As a result, BOS cost reductions have been equal to or greater than module cost reductions. A decline in BOS costs has occurred through greater integration of BOS components and a reduction in the overall number of parts required. Moreover, RD&D studies reveal that there are further cost efficiencies to be gained if, wherever possible, BOS assembly is standardized and shifted from the field to the factory.

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