
Solar Photovoltaics: Status, Costs, and Trends



An EPRI White Paper

December 2009

This report was prepared by:

Electric Power Research Institute
3420 Hillview Ave.
Palo Alto, CA 94304

Principal Authors and Principal Investigators:

Tom Key, Technical Executive, EPRI
Terry Peterson, Ph.D., Solar Power Consultant

Program Managers:

Tom Key, EPRI Enabling Integration of Distributed Renewables Program
Stan Rosinski, EPRI Renewable Generation Program

Acknowledgements:

Nanette Jones, Technical Assistant II, EPRI

This white paper is a corporate document that should be cited in the following manner:

Solar Photovoltaics: Status, Costs, and Trends. EPRI, Palo Alto, CA: 2009, 1015804.

Abstract

Solar Photovoltaics: Status, Costs, and Trends

This White Paper addresses the history, status, and trends of flat-plate solar photovoltaic power technologies in both crystalline silicon and thin-film forms. Perspectives are provided on the cost and performance, as well as, the materials used for producing PV modules. The major milestones and trends in PV power system development are described, looking back to the 1970's, and forward to the next 30 years. Current incentives and policies are also discussed with focus on utility engagement in PV power. Recent trends suggest that power companies will have a significant role in both distributed and utility scale applications. This raises the question "Is the electric industry ready?" The White Paper suggests some key evaluation parameters and a strategy check list for utilities. References to related EPRI research and a number of other useful documents are provided.

This renewable energy technology white paper was developed as a publicly available document under the EPRI renewable generation program. Its development was supported by members and funders of that program.

Contents

Abstract	iii
Introduction	1
Solar PV Technologies.....	1
Flat-Plate Photovoltaics	2
Photovoltaic Cell Types	2
Technology Status and Outlook	3
Deployment Trends.....	5
Solar Photovoltaic Applications	5
Recent Shift to Grid-Connected Systems	7
Deployments Currently Dominated by Europe	7
Manufacturing Shifting to Asia.....	8
Incentives and Policies	8
Cost and Economics	10
Distributed PV Performance and Costs	11
Utility-Scale PV Performance and Costs	11
Photovoltaic Module Costs	11
Installed PV System Cost Trends	12
Utility and EPRI Roles	13
Conclusions.....	15
References	15

List of Figures

Figure 1. Flat-Plate One-Axis Tracked Photovoltaic Arrays at Nellis Air Force Base, Near Las Vegas, Nevada	2
Figure 2. Historic Distribution of the PV Market by Cell Technology	2
Figure 3. Hobby-Scale Flexible Amorphous Silicon Module	3
Figure 4. Amorphous Silicon Thin-Film Modules Mounted on Tent Sheet (Source: PowerFilm, Inc.).....	3
Figure 5. Evolution of World-Record Laboratory Solar Cell Efficiencies for Various Material Technologies (NREL)	4
Figure 6. Diagram Depicting Conceptual Relationships Between Three “Generations” of PV Technologies	5
Figure 7. Typical Recent Grid-Connected Applications of PV Technology from kW to MW Scales	6
Figure 8. Worldwide Grid-Connected and Off-Grid PV Power [4]	7
Figure 9. Regional PV Shipments 2002-2008 (Source: Navigant Consulting Solar Outlook, February 2009).....	8
Figure 10. Worldwide Average PV Power-Module Selling Price vs. Cumulative Sales, 1976–2008, with Projection to 10 TW	12
Figure 11. PV Technology Trends from 1975–2040, Showing Evolving “Generations.” (Lab Cell Efficiencies from NREL)	13
Figure 12. PV Module and BOS (Non-Module) Costs Trends 1998-2008 (Source: LBNL [11])	14
Figure 13. Component Costs, as Percentage of Total PV Installed Costs (Source: LBNL [10])	14

List of Tables

Table 1. RPS Solar Requirement Estimates.....	9
Table 2. Indicative Prices of Installed PV Systems in Various Countries, 2008 [4].....	10

Solar Photovoltaics: Status, Costs, and Trends

Introduction

The heart of solar photovoltaic (PV) modules is a solid-state semiconductor device called a “solar cell” that converts sunlight into direct-current electricity. The technology was initially developed for the space program in the 1950s to power the first satellites. PV’s extreme simplicity, high reliability, and durability were keys for space applications but its high cost precluded most other uses. The energy crisis in the early 1970s renewed mainstream interest in PV, and its development expanded to include terrestrial power applications. At that time, PV’s R&D goals and funding sources shifted away from the space program to private/public sector collaborative efforts, which over the past 30 years resulted in a 95% decrease in module costs and a concurrent doubling in the typical PV system energy conversion efficiency.

With today’s growing environmental concerns, ongoing PV technology improvements and cost reductions, solar PV appears to be entering an era in which it will play an increasingly important role in meeting the world’s energy needs. In 2008, annual global module sales exceeded 5,400 MW [2] and they appear on track for a similar total in 2009, despite a worldwide financial slowdown since late 2008. This translates into a billions-of-dollars-per-year business for both module production and system installation. In recent years, favorable policies and subsidies in nations such as Germany, Japan, Spain, and the United States have stimulated the PV market and pushed annual growth to average 52% over the years 2003–2008. In fact, deployment growth of solar power today exceeds wind power and it is the fastest growing form of electricity generation on a percentage basis.

A solar cell’s power output depends on several factors, including its design and materials, the intensity of the solar radiation incident on it, and its temperature. Mono or polycrystalline silicon cells are most widely used today, but the cost of the highly purified silicon required for these remains a barrier and their manufacturing processes are relatively slow and difficult to automate. Due to these drawbacks, thin-film solar modules, which are not as efficient but are significantly less expensive and easier to scale to larger sizes and production volumes, are gaining market share.

Solar PV Technologies

There are two principal types of PV collection systems: flat-plate and concentrating. Flat-plate PV arrays can be mounted in a fixed orientation but they can also benefit from one- or two-axis tracking to face the sun. Concentrating PV (CPV) systems use lenses or mirrors to increase the amount of sunlight that reaches the solar cell. Such systems usually employ at least 100-times concentration, which requires precise, two-axis tracking to keep the sun’s rays focused on the cell. Although CPV systems have garnered increased investor and market interest in recent years, they still account for less than 1% of the PV market and this perspective will focus exclusively on the market-dominant flat-plate PV technologies.



Figure 1. Flat-Plate One-Axis Tracked Photovoltaic Arrays at Nellis Air Force Base, Near Las Vegas, Nevada

Flat-Plate Photovoltaics

Flat-plate terrestrial photovoltaic modules emerged in the 1970s and reached commercial status by the 1990s. Flat-plate PV designs connect the modules together into arrays in one of the following three configurations: fixed-tilt, single-axis tracking of the sun from east to west, or two-axis tracking (east-west and north-south). If the panels are fixed in orientation, maximum yearly production is obtained by tilting the panels toward the equator at an angle equal to the site's latitude. To increase summer production at the cost of decreased winter productivity, a tilt angle of latitude minus 15 degrees is often used. One-axis tracking can increase annual production approximately 20% over a fixed orientation. Two-axis tracking, in which modules are pointed directly at the sun throughout the day, increases annual production by approximately 30%. Until recently most flat-plate systems used fixed mountings and that continues to be true of roof-mounted systems. However, as system sizes of ground-mounted arrays have grown, there has been a trend toward using one-axis tracking for most crystalline silicon central-station plants. This has evidently been enabled by improvements in both tracker reliability and

costs, such that the increased system output more than compensates for its increased cost and maintenance.

Major trends in flat-plate PV designs focus on improving performance and lowering manufacturing costs. Module costs continue to decrease incrementally while module efficiencies increase. However, high-purity silicon remains relatively expensive and the supply for large-scale production has been an issue. Also, since PV output directly follows the sun's radiation, there is no energy storage and therefore the resource cannot be dispatched to follow demand requirements. In the near term, PV's daytime operation makes its energy more valuable on the grid than, say, nighttime wind power. But in the long term, some form of storage capability, together with a more flexible grid infrastructure, will be needed to enable higher PV grid penetration levels.

Photovoltaic Cell Types

The direct conversion of light into electricity in a solar cell, known as the photovoltaic effect, was discovered over 150 years ago but has only been practically developed since the 1950s. Solar cells employ semiconducting materials, such as silicon, that may be doped with

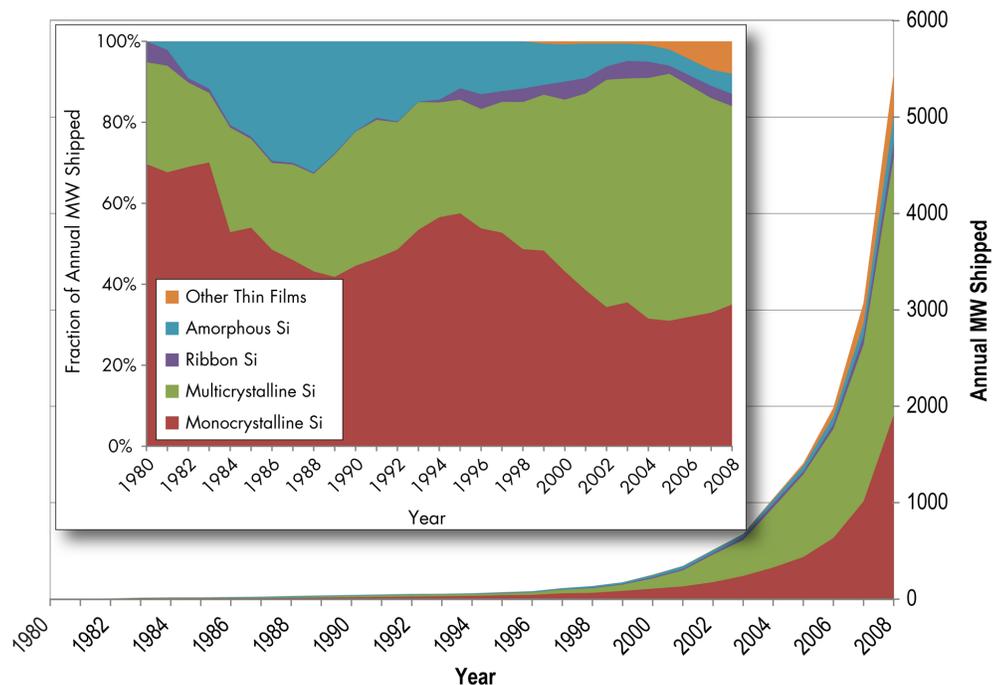


Figure 2. Historic Distribution of the PV Market by Cell Technology

other elements to change their conductivity. When adjacent semi-conducting layers with appropriate doping impurities are illuminated, a voltage develops between them that can be used to deliver a current to a load. Individual solar cells are combined into modules, or “panels,” that are connected in series and parallel to provide higher voltage and current levels. The dc power generated may be used directly or converted to ac by a power-conditioning unit.

Crystalline silicon is the traditional cell material for solar modules, and has maintained at least 80% market share of worldwide production for nearly all of the past 30 years; and, over 90% for much of the past decade, as shown in Figure 2. To date, crystalline silicon cells have achieved the greatest flat-plate module efficiency when illuminated at standard test conditions. In addition, crystalline silicon cells have the most highly-developed manufacturing processes. Typical commercial single-crystal (or “mono-crystalline”) silicon modules achieve solar-to-electric efficiencies of approximately 16-18%. The best commercially available silicon modules exceed 20% efficiency. Polycrystalline (also called multicrystalline) and ribbon silicon modules are slightly less expensive but also a few percentage points less efficient.

Thin-film solar cells are made from layers of semiconductor materials only a few micrometers thick that are deposited on a low-cost substrate such as plastic, glass, or metal foil, as seen in Figure 3. They use considerably less semiconductor material and their manufacturing techniques are well suited for mass production. In addition to reducing material costs, thin films make applications more flexible, as thin-film PV can be integrated into roofing tiles, windows, or even tent roofs, as seen in Figure 4. Thin-film cells significantly reduce cost per unit area, but also result in lower ef-

iciency cells, such that their costs per watt of output are similar to crystalline silicon’s.

Amorphous silicon is the most common type of thin film and has the longest operating history. Other materials include cadmium telluride (CdTe) copper indium diselenide (CIS), and copper indium gallium diselenide (CIGS). Other technologies under development include dye sensitized solar cells (DSSC) and organic polymer solar cells, but these are not yet close to commercialization for power generation.

Technology Status and Outlook

Thin-film module efficiencies have been improving over time, as have crystalline silicon’s. To date, the former have not matched the latter’s efficiencies, but they show potential for doing so over time. Present amorphous silicon modules have efficiencies of 6-9%. CIS/CIGS module efficiency now ranges from 8-12%, and CdTe modules are about 9-11% efficient. All of these technologies show real promise for ultimately replacing crystalline silicon as the PV workhorse technology. Indeed, amorphous silicon and CdTe both have over 1000 MW of commercial-scale production experience and, as Figure 2 shows, have been garnering increasing market share recently in the rapidly growing PV industry.

Given the recently rapid growth of both CdTe and amorphous silicon commercial sales, it is tempting to forecast a turnaround in the long-time market dominance of crystalline silicon shown in Figure 2. However, the underlying cost structure of both thin-film and crystalline silicon manufacturing has been rapidly evolving



Figure 3. Hobby-Scale Flexible Amorphous Silicon Module



Figure 4. Amorphous Silicon Thin-Film Modules Mounted on Tent Sheet (Source: PowerFilm, Inc.)

and neither camp appears to be approaching any absolute limits. Therefore, the PV market is destined to remain a vigorously contested horse race for a decade or two at least. In the much longer term there also are likely to be other entrants in that race, but the extreme difficulties involved in bringing brand-new PV technologies from the laboratory to the factory floor virtually guarantee that the leaders for the next 10 years or so will continue to include only crystalline silicon, amorphous silicon, CdTe, and CIGS.

PV technology is still evolving and has not reached mature commercial status. Without subsidies, it is currently best suited economically for small, off-grid installations and other applications where PV can often provide a service at the lowest cost. However, the presently predominant PV markets are driven by significant subsidies. One such market is that for residential and commercial rooftop retrofit installations of 1 to 500 kW each, driven also by growing public interest in “green power.” The “green” market motive also helps to stimulate the growth of building-integrated PV such as roofing materials and building facades, generally installed during new construction.

Large-scale bulk-power PV facilities are not now competitive with other intermediate and peaking supply technologies so it would seem unlikely for many large centralized PV facilities to be built in the near future, outside of markets where they are specifically incentivized by policy-driven subsidies, such as in Germany, Spain, Portugal, and several other European Union countries. However, the adoption of Renewable Portfolio Standard (RPS) requirements in the U.S., together with extension of the Federal 30% solar investment tax credit to utilities, appears to be fueling interest in central-station PV. Two multi-megawatt PV systems were commissioned in the U.S. in the first half of 2008 and multiple hundreds-of-megawatt scale PV agreements have already been announced by California utilities PG&E and SCE.

The evolution of most of the principal PV cell technologies shown in Figure 5 suggests two important conclusions about the future of the industry. First, there is a substantial time lag of about 20 years between laboratory efficiency achievements and their appearance in flat-plate commercial products. This underscores the difficulty of scaling up square-centimeter laboratory cells to

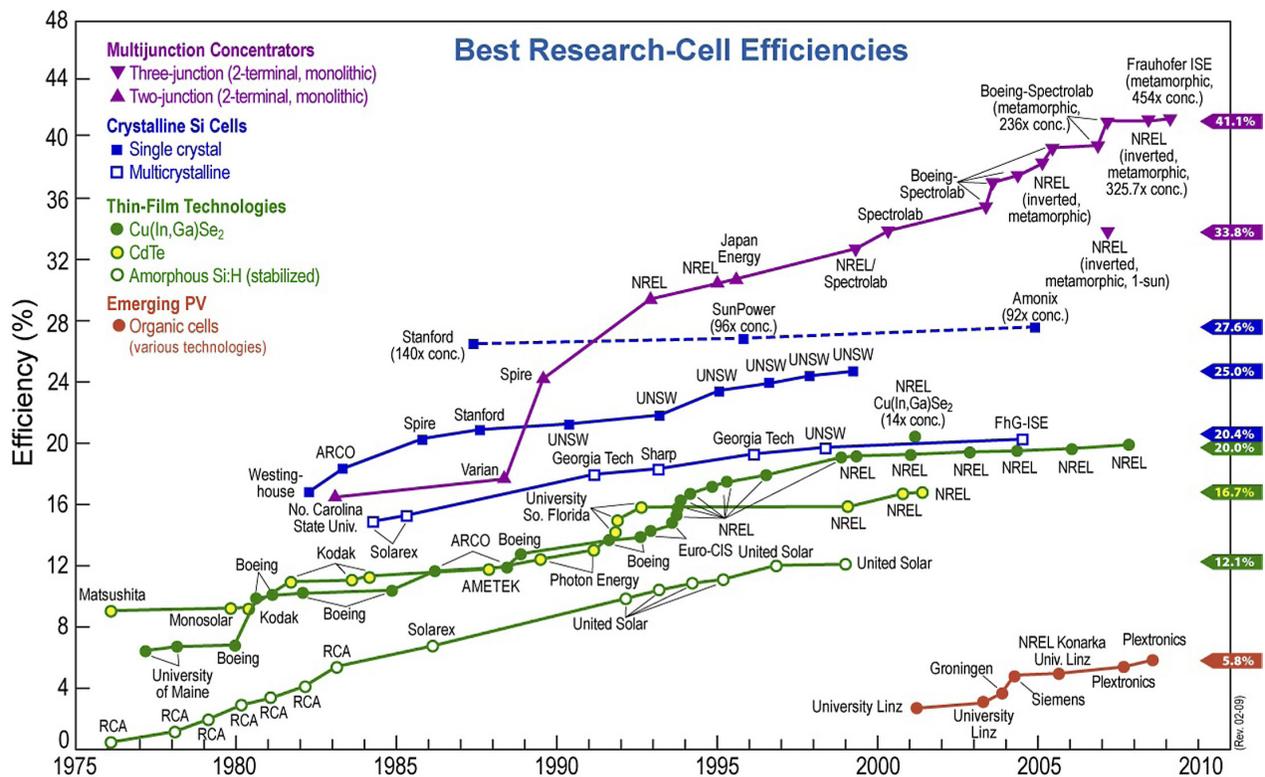


Figure 5. Evolution of World-Record Laboratory Solar Cell Efficiencies for Various Material Technologies (NREL)

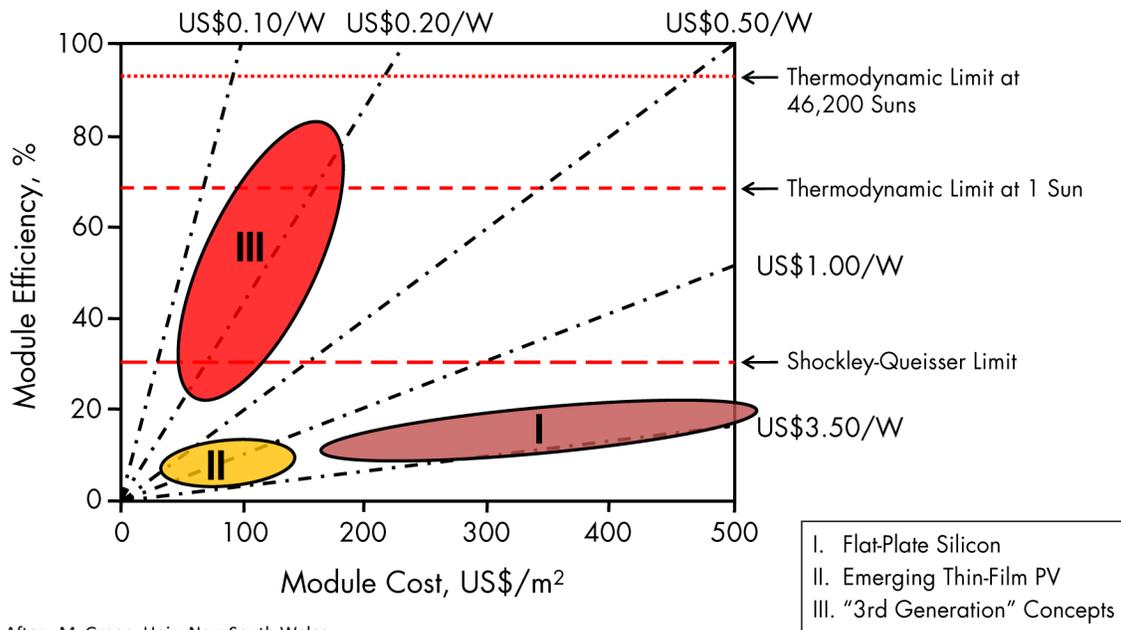


Figure 6. Diagram Depicting Conceptual Relationships Between Three "Generations" of PV Technologies

square-meter products. Notably, this observation does not apply to the high-efficiency multijunction cells now used in concentrating PV applications, where such enormous scale-up in cell dimensions is not required for commercial production.

The second conclusion from Figure 5 is that nearly all thin-film technologies have substantial room for performance improvement, given the current difference of roughly 100% between commercial modules and the record cells compared to about 25% in the corresponding crystalline silicon cases. This is clearly a consequence of the relative immaturity of thin-film PV manufacturing.

Looking to the future, a number of concepts show promise for advancing the performance of PV devices by a factor of two or three from those in present-day commercial modules. Collectively, these advanced devices are known as "Third Generation Photovoltaics" [3]. Figure 6 illustrates the performance and cost relationships between these third-generation concepts and current thin-film and crystalline silicon technologies. Although most of the third-generation concepts have not even reached the stage of laboratory demonstration, the one known as the "multijunction cell" can be found in some of today's commercial amorphous silicon modules and specialized cells made for concentrating PV systems.

This multijunction concept involves making a device with two or more working junctions that are stacked one atop the other so that the sunlight reaches the lower junction(s) after being filtered through the upper one(s). Such a structure provides the possibility of higher conversion efficiency because it allows the more energetic photons of the solar spectrum to be harvested separately from the lower-energy ones. In theory, multijunction PV devices may be up to 86% efficient at converting sunlight to dc power. In practice, multijunction amorphous silicon modules have shown higher efficiency and greater stability than single-junction amorphous silicon modules. Multijunction concentrator cells made using semiconductor alloys related to gallium arsenide and indium antimonide hold the present world's record for solar energy conversion efficiency at over 41%.

Deployment Trends

Solar Photovoltaic Applications

There are four main applications for solar PV power systems: grid-connected centralized power stations, grid-connected distributed PV, off-grid building power systems, and off-grid PV-DC loads and appliances. Off-grid PV power systems—those that are not

connected to a utility electricity network—dominated installations until the late 1990s, but they now represent a minor fraction of the global PV market. They provide power to a wide range of relatively low-power loads such as telecommunication, battery charging, lighting, refrigeration, and water pumping. Facility power systems are typically at a kilowatt level and can range from several hundred watts to a few kilowatts.

Grid-connected distributed PV systems, such as the Figure 7 installations in Sacramento, Oakland, and Sapporo City, can provide supplemental power to a utility customer's loads, displacing retail power sales, or they may be directly tied to the electricity network with a separate meter. The direct network connection typically applies to cases where there is a "feed-in tariff" that pays a market premium for solar generation, while the supplemental-power connection is used when there is no premium available. Distributed systems may be on customer property or public and commercial buildings.

Grid-connected centralized PV power stations, also called central-station PV, are larger-scale and ground-mounted, such as the Bavarian system in Figure 7. As of late 2008, the 14-MW PV array at

Nellis Air Force Base, Figure 1, was the largest central-station PV installation in the United States and the largest worldwide was a 60-MW plant located in Olmedilla, Spain. In July 2009, there were over 1000 PV plants larger than 1 MW each in the world. The 50 largest of those were all over 10 MW each and totaled 982 MW. The majority (38) were installed in Spain during the explosion of the PV market there in 2008, followed by 4 each in Germany and South Korea and 2 each in Portugal and the U.S.

Several large-scale U.S. PV projects were recently completed, while more—much larger—systems are planned. Semptra's (First Solar technology) 10-MW El Dorado project went online in Nevada in 2008. FPL's 25-MW facility in DeSoto County, Florida was the largest in the country when it began operation in October 2009. A 10-MW farm at Kennedy Space Center is to be completed in 2010. In New Mexico, a 30-MW thin-film PV project using First Solar modules is expected to be online in 2010. Southern California Edison completed the first two 1-MW projects of its 5-year 500-MW program for commercial rooftop PV, which is to be 50% utility



540 kW of PV Canopies in Sacramento, CA
(Source: PowerLight Corp.)



0.9 MW PV on FedEx Hub, Oakland, CA
(Source: PowerLight Corp.)



2 kW PV Rooftops in Sapporo City, Japan
(Source: International Energy Agency)



6.3 MW Solarpark in Mühlhausen, Bavaria
(Source: PowerLight Corp.)

Figure 7. Typical Recent Grid-Connected Applications of PV Technology from kW to MW Scales

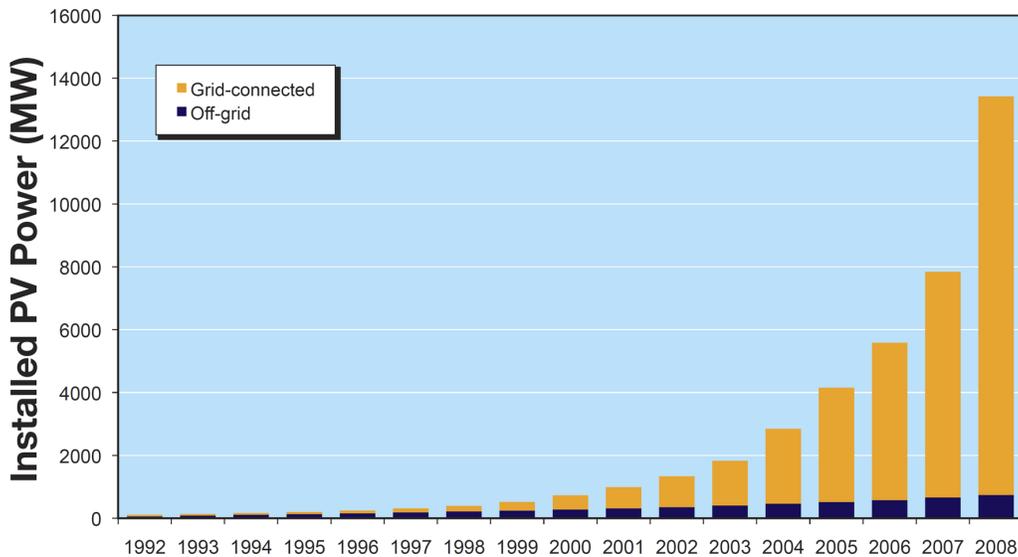


Figure 8. Worldwide Grid-Connected and Off-Grid PV Power [4]

owned. Pacific Gas & Electric announced a similar 500-MW program as well as plans for two central-station PV installations. The latter comprise the 550-MW Topaz Solar Farm and the 250-MW California Valley Solar Ranch and are expected to be the largest PV systems in the world when constructed and operational in 2013 [5].

Recent Shift to Grid-Connected Systems

At the end of 2008, cumulative installed PV capacity totaled more than 14 gigawatts (14,000 megawatts) worldwide, according to the International Energy Agency (IEA) [4]. Approximately 5.5 GW of PV was installed in 2008, an increase of about 140% over the previous year. The IEA data clearly indicate tremendous growth in grid-connected PV since the mid 1990s when it was the minority of the market. This trend has continued such that grid-connected applications accounted for about 94% of cumulative installations by 2008. Off-grid applications have continued to grow worldwide, albeit less vigorously than grid-connected systems. Figure 8 illustrates the growth in PV capacity for both off-grid and grid-connected applications.

In the U.S., grid-connected PV capacity installation increased 58% in 2008 over 2007. The U.S. added 342 MW of PV in 2008, including 292 MW of grid-connected capacity, which brought the total installed grid-connected PV capacity to over 1,000 MW [5].

Based on market and policy considerations, grid-connected PV systems for commercial, industrial, and residential uses appear to be entering a period of long-term, accelerated growth after recovery from 2009’s recession. Navigant Consulting estimates future output to grow vigorously through 2012, albeit not at the 43% they were projecting prior to the 2009 economic slowdown [6].

Deployments Currently Dominated by Europe

The U.S. was the first major center of PV system deployments, comprising over 40% of the total market from the 1970s until the early 1990s. Beginning in 1994, the 10-year-long Japanese Sunshine Project stimulated both production and deployments of PV in Japan, making it the world leader in both categories by 1997. However, in 1993 the German city of Aachen initiated a novel tariff requiring its electric utility to pay handsome premiums for PV-generated power. The Aachen “feed-in tariff” model soon spread throughout the country and propelled poorly sunlit Germany into position as the globally dominant market. German PV installations comprised about half of the world’s cumulative total by 2007, according to the IEA [4]. This leadership was briefly overshadowed in 2008 by a virtual explosion of PV sales in Spain, driven by a feed-in tariff rule very similar to the German one. However, the Spanish market contracted precipitously in 2009 as a result of changes in its solar tariffs and Germany re-emerged as the worldwide leader.

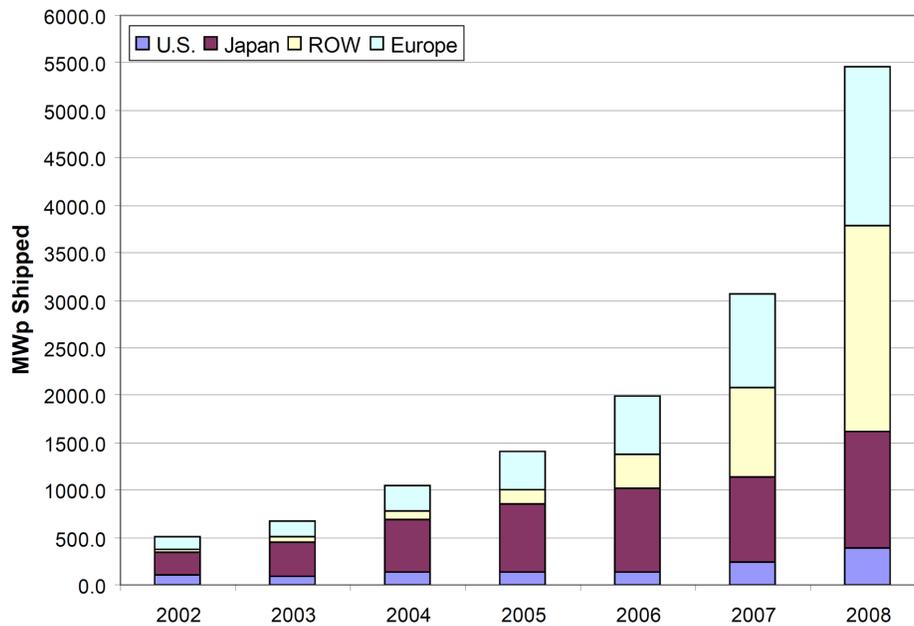


Figure 9. Regional PV Shipments 2002-2008 (Source: Navigant Consulting Solar Outlook, February 2009)

According to Navigant Consulting’s figures on regional demand, more than 5 GW of PV modules were shipped globally in 2008. Japan accounted for about 5% of installations, Europe (primarily Germany and Spain) had 78%, the U.S. had 8%, and the remaining 9% was divided among the rest of the world—where most of the two billion people without electricity today live [2]. Government announcements during 2009 of new solar-power initiatives in both China and India, touting respectively 10- and 20-GW deployments of solar power by 2020, appear to promise significant PV growth in those countries over the next decade. Meanwhile, PV deployment is growing in several U.S. States and many industry observers expect the U.S. to emerge as the leading market within the coming decade.

Manufacturing Shifting to Asia

Figure 9 shows how Japan dominated PV production in the early years of this decade, as it had since the latter 1990s. It also illustrates how European (primarily German) PV manufacturing took off, beginning in the first half of this decade, while U.S. growth has relatively languished for the past half-dozen years. Finally, it shows the dramatic growth of output from Asia (led by China) beginning in 2006.

In 2008, leadership in PV manufacturing shifted from Europe to the “rest of the world” (ROW) which includes China, Malaysia, the Philippines, and India. These countries are leaders in low-cost manufacturing while also offering subsidies to non-domestic manufacturing companies. A significant number of cell and module manufacturers are in China due to government support for domestic manufacturing.

Incentives and Policies

The U.S. federal government, acting through the Department of Energy (DOE), has instituted several programs through the years to support PV research and development, subsidize its use, and plan for its future. The Federal “Million Solar Roofs” Initiative, begun under the Clinton administration, aims to install one million solar energy systems—including PV, water heating, and space heating—on the rooftops of American homes and businesses by 2010. The initiative includes federal procurement programs, technology grants, and lending programs.

In 2006, the Bush administration launched the Solar America Initiative (SAI) at the DOE, whose goals are to accelerate PV deployments and conduct RD&D targeted to bring PV costs to “grid parity” by 2015. The DOE PV budget was roughly doubled as a result

of the SAI program and new projects have been launched. These are comprised primarily of industry-led short-term efforts to rapidly scale up current PV technologies, but they also include public-outreach educational projects, a “technology incubator” program to help startup companies move from laboratory-scale pilot lines into early commercial-scale production, and a small amount of exploratory research into novel concepts. Several states also have programs encouraging the development of renewable energy. In many cases, a combination of state and federal incentive, rebate, or loan programs can pay a significant share of a PV system’s cost.

In addition, solar requirements embedded in renewable portfolio standards (RPS) are also fueling PV development. The National Database of State Incentives for Renewable Energy (DSIRE) at www.dsireusa.org provides up-to-date information on state financial and regulatory incentives that are designed to promote renewable energy technologies. DSIRE showed for example that, as of late 2009, 36 States plus Washington DC and Guam had

Table 1. RPS Solar Requirement Estimates

State	2010	2025	2025 Solar Generation as a % of State Load
Arizona	110 MW	1,600 MW	2.0%
Colorado	29 MW	160 MW	0.4%
Delaware	0.5 MW	190 MW	1.4%
Maryland	14 MW	1500 MW	2.0%
Nevada	76 MW	180 MW	0.6%
New Hampshire	4 MW	35 MW	0.3%
New Jersey	210 MW	1,600 MW	2.1%
New Mexico	64 MW	420 MW	3.1%
New York	10 MW	15 MW	0.0%
North Carolina	5 MW	280 MW	0.2%
Pennsylvania	25 MW	690 MW	0.5%
District of Columbia	0.5 MW	54 MW	0.4%
Total	550 MW	6,700 MW	-

Estimated cumulative solar required to meet state RPS solar and DG set-asides.

Source (reprinted): Wisser, Ryan and Galen Barbose. “Renewable Portfolio Standards in the United States.” Lawrence Berkeley Labs, April 2008.

enacted RPS requirements and seven had regulations specifying the minimum amounts of new electric generation, by a certain date, that must be from distributed or solar resources, known as solar set asides.

The solar industry achieved some significant U.S. national policy victories in late 2008. The Emergency Economic Stabilization Act of 2008 (EESA), passed in October 2008, extended the 30-percent solar Investment Tax Credit (ITC) for eight years, lifted the cap for residential PV installations, allowed application of the tax credits against the alternative minimum tax (AMT) and removed the prohibition against utilities’ use of the ITC. This long-term policy stability will help companies in the U.S. solar market make longer-term investment decisions and attract better financing.

Germany and Japan have had active and generous government-sponsored and-mandated long-term incentive programs. As a result of these, both countries are leaders in PV manufacturing and Germany ranks first in the world in cumulative installed PV capacity. The United States, with far more land and sunshine than either of these, trails both in manufacturing and deployments. Spain catapulted to the world’s largest PV market in 2008, driven by incentives that motivated over 2.5 GW of installations that year. The Spanish government reacted by capping incentive payments in 2009 at 500 MW. The ensuing market disruption is evidently leading to a decline in the country’s annual addition in 2009 to even less than that amount.

In past years many regulated U.S. utilities have added renewable energy technologies to their supply portfolios through purchase power agreements (PPA) with third party independent power producers (IPP). As renewable energy has been a small part of electricity generation and has been perceived as higher capital costs and technology risk, PPAs have been more popular than utility capital investments. The supplier accepted technology risks, which it incorporated into the PPA costs. These supply costs were passed directly through to utility customers; the utility recovers its PPA costs as an expense. It was thought that this arrangement added no cost to consumers or purchasing energy from renewable resources since the utility held no risk, and therefore required no specific recovery for any risks in the PPA.

Recently rating agencies have changed how they treat these transactions relative to the utility’s investment rating by imputing debt

Table 2. Indicative Prices of Installed PV Systems in Various Countries, 2008 [4]

Country	Off-grid (USD per W)		Grid-connected (USD per W)	
	<1 kW	>1 kW	<10 kW	>10 kW
Australia	15–25	12.5–18.3	7.5–10.8	5.8–8.3
Austria	8.8–22.1	8.8–22.1	7.1–8.5	7.1–8.1
Canada	14		5.6–6.5	5.6–7.5
Germany			5.7–6.6	5.4
Denmark	13.7–17.6	29.4–39.2	6.9–16.7	9.8–19.6
France			10.3–12.2	7.5–8.8
Great Britain	9.1–13.6	7.3–13.8	6.2–18.5	7.3–14.5
Israel	9.0	10.0	6.0–7.5	
Italy	14.7–19.1		8.1–9.6	6.2–8.1
Japan			6.9	5.2
Korea (South)			6.1–8.4	8.4
Malaysia			7.2	7.2
Mexico	17.0	14.7	12.4	8.5
Norway	22.1–31.9		15.9–21.2	
Portugal		11.8–14.7	7.4–8.8	6.2
Spain	16.8–21.2	14.3–16.8	10.3–11.0	8.4–8.8
Sweden	13.6		14.5	10.2
Switzerland	20.8	15.5	8.8–9.4	7.6–7.9
Turkey	11.8–13.2	8.8–11.8	6.6	5.9
United States	7–9	8–10	7–9	6.5

Notes: Additional information about the systems and prices reported for most countries can be found in the national survey reports on the IEA PVPS website. Excludes VAT and sales taxes. More expensive grid-connected system prices are often associated with roof integrated slates or tiles or one-off building integrated designs or single projects, and figures can also relate to a single project.

on these transactions even though energy is only paid for as it is generated by the IPP. PPAs, they reckon, result in some assumed risk that is transferred back to the utility by virtue of the PPA. Debt imputation by rating agencies limits the available cash to make capital investments, thus raising the cost of capital to the utility. [17]

To remedy higher cost and resulting earnings shortfall, utilities could petition their regulators to adjust earnings to allow for a return on a PPA to offset the rating agencies' imputed debt. As RPS requirements grow, this treatment of risk will raise the cost of renewable energy. However, the cost associated with imputed debt associated with PPAs may tip the balances in favor of utility investment in renewable assets rather signing purchase agreements. It may be more advantageous to consumers for utilities to

become owners and operators of these technologies with costs and return on assets allowed in the rate base. Clearly the relative maturity of PV along with high capital costs and relatively low O&M will be determining factors in considering utility renewable asset investments and rater-basing. For more information about utility-ownership and regulatory filings related to PV see [18].

Cost and Economics

As solar PV technologies continue to evolve, significant cost reductions are expected to continue as a result of improving power conversion efficiencies, development of low-cost cell fabrication processes, and increasing cell production volume with attendant economies of scale. Table 2 provides a sample of 2008 PV in-

stalled-cost data collected by IEA for various countries categorized by system size [4]. It illustrates the ranges in costs between different regions as well as between plant sizes. Another very good online resource for illustrative data on U.S. PV installations is the NREL database called The Open PV Mapping Project [9].

Distributed PV Performance and Costs

The fundamental PV technology is the same for distributed and central-station PV systems, but costs and economic considerations differ between them. In the former case, some or all of the cost may be borne by customers interested in benefiting from on-site distributed generation or in supporting clean renewable technology. Depending on local electricity prices and available rebates, subsidies, or incentives, the payback period for a typical residential-scale PV system often exceeds a decade. A distributed PV system may also be owned by an energy company interested in providing grid support in critical areas, exploiting new business opportunities, or complying with policy demands such as renewable portfolio standards. Because PV is highly modular, distribution companies can precisely deploy it in optimal locations and capacities or work with customer-owners to do so. Other purchase or lease arrangements may be beneficial to customers, utilities, or both.

To accurately evaluate the costs and benefits of a possible distributed PV project, the consumer must:

- Obtain detailed cost and performance data from the PV system or module manufacturer
- Acquire meteorological data from a representative ground station
- Simulate the production of the PV system, taking into account sun angles and module orientation
- Determine hourly impacts on consumption from the electric utility and related electricity cost
- Calculate monthly energy and/or demand savings using their specific utility tariff structure
- Calculate the financial impacts and applicability of various buy-down programs, tax credits, and financing terms

Distributed PV production models and financial calculations are complex and the factors involved vary widely. It is impractical to attempt to construct a single example representative of all distributed PV systems. There are many computer models available to assist in these calculations, with the U.S. Department of Energy's Solar Advisor Model perhaps having the best combination of ease-of-use and comprehensiveness [12]. A general observation that can be made is that there are today significant markets where the subsidized cost to the PV end user appears attractive versus local utility rates to many potential customers.

Utility-Scale PV Performance and Costs

Photovoltaic power plants have long been designed as distributed-generation resources at the watt to tens-of-kilowatt scale. However, they are now also appearing more frequently in central-station configurations in the tens-of-megawatt range, and even larger plants are on the drawing boards of several developers and system integrators. Fixed costs, such as engineering, applying for subsidies, and project management can make up a smaller percentage of larger systems. In addition, equipment such as inverters can be less expensive in larger sizes. Economies of scale are not linear, however, as the main cost element of the system—the solar panel—tends not to drop significantly with scale for systems in the MW range. Thin-film modules are generally less costly than crystalline but their lower efficiencies, which require larger balance of system (BOS) costs, tend to offset that advantage. Tracking systems maximize the power output of a particular PV array but also add to its cost and mechanical complexity.

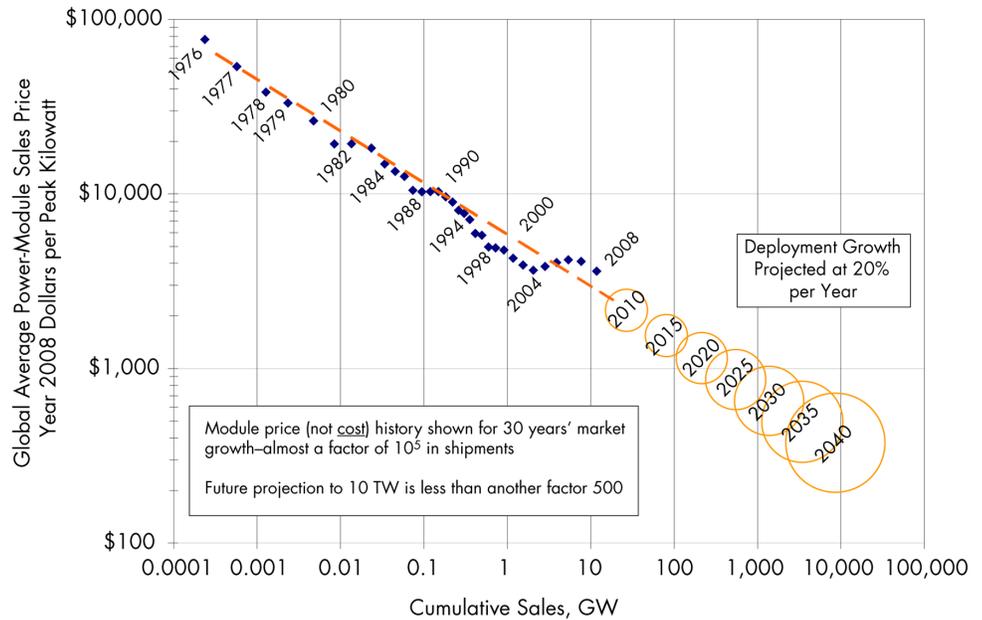
Photovoltaic Module Costs

Modules typically constitute half of the cost of PV systems. Figure 10 shows the evolution of worldwide PV module average selling prices from 1976 through 2008 in constant year-2008 dollars [7, 8]. The figure presents these data in the form of an “experience curve,” where the average sales price is plotted versus cumulative sales volume. This format was chosen to show the clear power-law behavior of historical module prices, where the average selling price has declined by about 20% with each doubling of sales. Note that the right end of the figure's abscissa, at 10,000 GW, is about ten times the total installed U.S. electric generation capacity today, while the 2008 data point is a little over one percent of that.

In the 30-year timeframe of the historic data in Figure 10, the total market size has grown about 100 thousand fold, while prices have fallen more than 90%, and typical system efficiency has roughly doubled. PV's progress the rest of the way toward 10,000 GW represents about another 500-fold growth.

From 2004 to mid 2008, a short-term constriction in high-purity silicon feedstock plus an ongoing strong demand pushed up module prices by about 10%. This fueled faster growth in the thin-film PV sector. However, the higher prices spurred massive investment in silicon production and innovations in cell production to reduce silicon usages, as well as expansions in module manufacturing. Since the third quarter of 2008, the increased feedstock supply plus softening demand caused by global recession resulted in silicon module prices falling over 30%, such that it appears likely for the 2009 point on the experience curve to fall very close to the historic trend line. While this may produce a shakeout in PV manufacturing and eliminate some of the high-cost producers, it will certainly result in significant savings to consumers and possibly rekindle demand from the 2009 recession level.

The widening circles in Figure 10, projecting PV deployments to 2040, are based on an assumed demand growth averaging 20% per year, together with ongoing "learning" that enables prices to continue their historic decline. This envisions a simple continuation of silicon's past price-setting role as the dominant player in the PV market. This projection is, of course, speculative but it is commensurate with PV's 30-year historic market growth and conservative compared with the last 10 years of PV market and technology developments that have averaged about 40% growth per year. From the point of view of likely technology advancements, given the recent emergence of multiple commercial thin-film PV products and the prospects for efficiency gains with concentrating PV suggested in Figure 11, the extrapolation may well prove to be even pessimistic.



ASP data source: P. Mints, Navigant Consulting PV Service Practice T.M. Peterson 12/06/09

Figure 10. Worldwide Average PV Power-Module Selling Price vs. Cumulative Sales, 1976-2008, with Projection to 10 TW

Installed PV System Cost Trends

Lawrence Berkeley National Laboratory (LBNL) released in early 2009 a comprehensive summary of installed cost trends for grid-connected solar PV systems in the U.S. from 1998 through 2007 [10] and, in October 2009, a follow-up report, covering through 2008 [11]. The latter report is based on installed-cost data from over 52,000 residential and non-residential PV systems, totaling 566 MW of capacity and representing 71% of all grid-connected PV capacity installed in the U.S. through 2008. A key finding of these summaries is that, while the overall average costs have declined in the study period, there are significant regional variations in costs and incentives that are in effect. These variations are larger than the cost changes over the ten-year study period and arise from regional differences in incentive policies, installation code requirements, and degree of installer experience. Another finding was that there are evidently significant economies of scale, with systems 500–750 kW averaging 30% lower cost than systems under 2 kW.

Figure 12 shows that average installed costs per dc watt for PV systems in 2008 dollars have declined from \$10.80 in 1998 to \$7.50

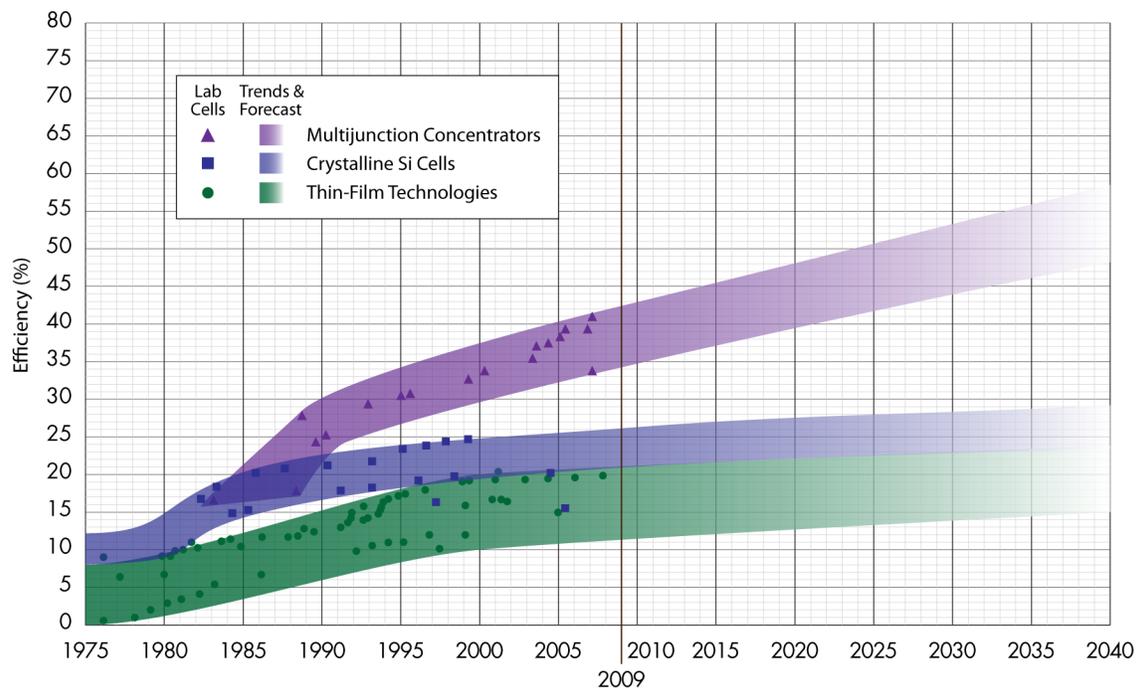


Figure 11. PV Technology Trends from 1975–2040, Showing Evolving “Generations.” (Lab Cell Efficiencies from NREL)

in 2008. It also shows a continuation of the long-term trend of system costs being split approximately 50:50 between PV modules and the balance of the system. This trend has persisted through the past three decades, during an overall 95% cost reduction, despite periods of a few years when one or the other of those components has failed to decline or has even increased (as seen in Figure 12 also).

A 2008 survey of PV installers reported the typical percentage contribution to total cost for a variety of specific cost components (e.g. modules, inverters, installation labor, etc.), shown in Figure 13. As seen typically, PV module costs were about 50% of total installed costs, while inverters represented approximately 6-7%. The survey also indicated that non-module, non-inverter costs such as installation labor, materials, and regulatory compliance represented a greater percentage of total installed costs for residential systems than for larger, non-residential systems.

Utility and EPRI Roles

Future deployment of solar photovoltaic systems is expected to challenge the utility industry in several ways. The first will be

enabling the electric grid to effectively integration and distribute PV energy to electricity users. The second is to realize the full value of the electric grid and the PV power systems by developing new business models for these distributed resources. EPRI has addressed some different approaches to meeting these challenges in other white papers [14,15] and in the article *Finding a Bright Spot* [16].

A recent survey report from Emerging Energy Research notes that U.S. utilities have announced more than 4.8 GW of large PV projects and predicts that they will add 21.5 GW of PV by 2020, up from 77 MW of utility-sponsored PV projects operating as of November 2009 [13]. Such dramatic growth implies that PV deployment will soon become a much greater daily concern for utilities than heretofore.

Related to these challenges, a number of utility leaders are considering if they are ready for higher levels of PV deployment and are reviewing their strategy and plans. In one case the following “top ten” check list items were identified:

1. Developing an overall strategy for orderly PV adoption and rollout

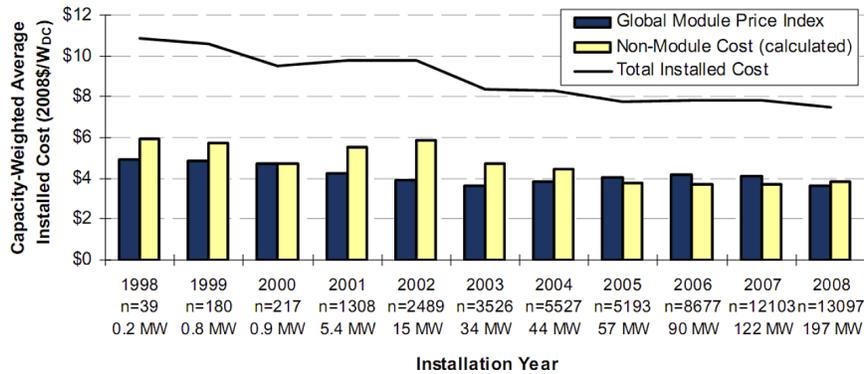


Figure 12. PV Module and BOS (Non-Module) Costs Trends 1998-2008 (Source: LBNL [11])

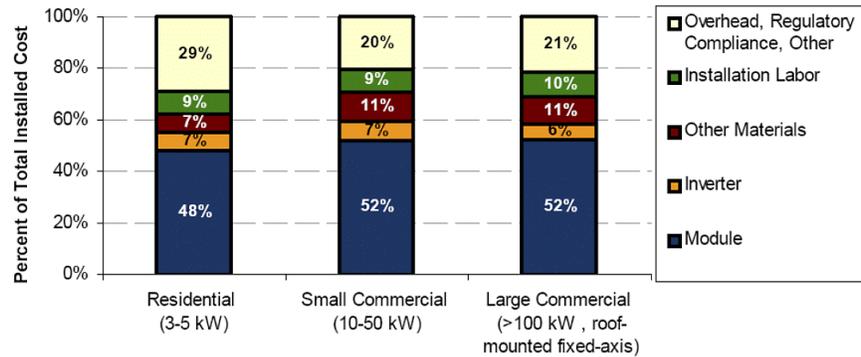


Figure 13. Component Costs, as Percentage of Total PV Installed Costs (Source: LBNL [10])

2. Designing a business plan to maximize company and rate-payer PV benefits
3. Assigning necessary internal resources to address new infrastructure demands
4. Arranging PV industry partners to stay on the leading edge of applications
5. Selecting a solar applications menu to assist in orderly business expansions
6. Discovering grid-integration issues and opportunities to avoid costly oversights
7. Designing PV energy rates and incentives to speed implementation and ensure equitable earnings
8. Filing for rate recovery to avoid costly implementation delays
9. Planning technology and application demos for internal and external learning

10. Reaching out to educate and engage customers to enhance relationships and raise corporate image

EPRI can be a valuable partner and resource in many of these activities through the [EPRI Solar Electric Interest Group \(SEIG\)](#) as well as collaborative R&D opportunities. Research related to enabling higher penetration, understanding detailed difference in the cost and performance of different PV technologies and applying new business models are all growing parts of EPRI's PV R&D portfolio.

Some research activities that are currently underway at EPRI include conducting a market assessment of the Concentrating PV industry, supporting the DOE's development of a Solar Vision for 2030 that examines PV's future role among other generation technologies, and a side by side PV module evaluation in Birmingham Alabama. Also EPRI is collaborating with SEPA and DOE to pave the way for communication between PV inverters and the distribution utility. EPRI's Knoxville distributed generation test facility

will be used to conduct PV inverter testing to evaluate different inverter and array configurations while modeling distribution feeder interactions. Other grid-integration projects include studies of feeder effects, high-resolution PV monitoring, and future O&M needs. For more information about EPRI's capabilities visit the SEIG website: www.epri.com/seig

For more information, contact Tom Key at tkey@epri.com.

Conclusions

Worldwide installation of PV systems has been growing at a rapid pace in recent years, driven by a combination of government incentives and popular support for clean energy. A key goal of the incentive programs has been to drive down costs by increasing production volume. PV costs have indeed declined substantially over the long term, for both module and non-module costs, and they show no signs of slackening the pace beyond short periods of infrastructure regroupings, such as the recent 3-year shortage of high-purity silicon feedstock. Even the 2009 global recession has evidently hit the PV industry relatively mildly, softening demand in the first half of the year but showing many signs for resumption of vigorous growth in 2010. Existing regional variations in average installed costs suggest that there is much to be gained globally from learning best practices in system installation and interconnection.

Many experts are predicting a blossoming of the U.S. market over the next few years, as installed prices reach substantial parity with conventional alternatives and the true potential of the domestic solar resource is better appreciated. Large-scale commercial PV and central-station utility-scale PV will most likely become the dominant growth market; however, the relatively high value of displaced retail kWh will probably stimulate ongoing strong growth of the residential and commercial markets as well.

References

1. *Renewable Energy Technical Assessment Guide—TAG-RE*: 2008. EPRI, Palo Alto, CA. 2008. 1015801.
2. *Solar Outlook: Bimonthly Photovoltaic Industry Update*. Navigant Consulting, Palo Alto, CA: February 2009. SO2009-1.
3. Green, M.A. *Third Generation Photovoltaics: Advanced Solar Energy Conversion*. Springer-Verlag, Berlin, Germany: 2003.
4. *Trends in Photovoltaic Applications: Survey Report of Selected IEA Countries between 1992 and 2008*. IEA, Photovoltaic Power Systems Programme: August 2009. IEA-PVPS T1-18:2009.
5. U.S. Solar Industry Year in Review 2008. SEIA, Washington, D.C.: 2008. <http://www.seia.org/>
6. *Solar Outlook: Quarterly Photovoltaic Industry Update*. Navigant Consulting, Palo Alto, CA: February 2008. SO2008-1.
7. *Analysis of Worldwide Markets for Photovoltaic Products and Five-Year Application Forecast 2006/2007*. Navigant Consulting, Palo Alto, CA: August 2007. NPS-GLOBAL2.
8. *Photovoltaic Manufacturer Shipments & Profiles*. Strategies Unlimited: September 2003. SUPM 53.
9. The Open PV Mapping Project, National Renewable Energy Laboratory, <http://openpv.nrel.gov/>
10. *Tracking the Sun: The Installed Cost of Photovoltaics in the U.S. from 1998-2007*. LBNL, Berkeley, CA: February 2009. LBNL-1516E.
11. *Tracking the Sun II: The Installed Cost of Photovoltaics in the U.S. from 1998-2008*. LBNL, Berkeley, CA: October 2009. LBNL-2674E.
12. U.S. DOE Solar Advisor Model, www.nrel.gov/analysis/sam/
13. *Emerging Energy Research, US Utility Solar PV Markets and Strategies: 2009-2020*, <http://www.emerging-energy.com/>, accessed 13 December 2009.
14. *Solar Photovoltaics: Expanding Electric Generation Options*, EPRI, Palo Alto, CA. 2007. 1016279.
15. *Distributed Photovoltaics: Utility Integration Issues & Opportunities*, EPRI, Palo Alto, CA. 2008. 1018096.
16. T. Key, Finding a Bright Spot: Utility Experience, Challenges, and Opportunities in Photovoltaic Power, IEEE Power & Energy Magazine, May/June 2009
17. The Brattle Group. Final Draft: 3-Jun-08. *Understanding Debt Imputation Issues*; Edison Institute White Paper. Edison Electric Institute.
18. *Distributed Photovoltaic Generation for Electric Utilities*: SEPA Report #04-09, EPRI Study Published by Solar Electric Power Association, February 2009.

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute Inc., (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, non-profit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent more than 90 percent of the electricity generated and delivered in the United States, and international participation extends to 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together...Shaping the Future of Electricity

Electric Power Research Institute

3420 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

© 2009 Electric Power Research Institute (EPRI), Inc. All rights reserved. Electric Power Research Institute, EPRI, and Together...Shaping the Future of Electricity are registered service marks of the Electric Power Research Institute.

 Printed on recycled paper in the United States of America