Advances in Solar Photovoltaic Technology: An Applications Perspective

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Abstract— **Advances in photovoltaic module technology, inverters, system installation practices, and design standards are improving the performance of PV systems and have led to PV becoming established as a strongly competitive energy source for off-grid energy applications. PV is also on the cusp of becoming competitive in grid connected configurations and is currently experiencing strong growth in this type of application. Substantially reduced PV module cost and higher module efficiency compared to products of just a decade ago are playing a key role in this expansion. The introduction of modern inverters that are more efficient, have higher reliability, and improved utility system interface features are also facilitating market growth. In addition, experience gained from hundreds of thousands of PV installations over the past decade, as well as a maturing base of PV service providers, system integrators, and new industry design standards has led to improved designs and economies in the installation of PV systems. Overall, PV energy costs have fallen by a factor of about 2 over the past decade and the prospects for continued improvement are strong. This presentation reviews advances in PV technology and the role they are playing in its expansion.**

Index Terms—**Photovoltaic (PV), PV module, Inverter, DG Interconnection**

I. Introduction

PHotovoltaic (PV) energy offers substantial benefits for society in that it is a zero-emission energy source, is inexhaustible, and is of domestic origin offering much greater security than imported energy sources. However, the high cost of PV energy has until the last decade limited economical PV uses to relatively specialized off-grid low energy consumption applications. Now, thanks to ongoing improvements in PV technology and improvements in balance of system components, as well as experience gained from hundreds of thousands of system installations, PV energy cost and performance have improved to the point where a large off-grid market is flourishing and the on-grid market is nearly economic. The main technical factors over the past decade that have led to improved PV system performance include:

- Improved PV module/cell manufacturing techniques and scale that have lowered PV module costs and resulted in higher module efficiency
- Improved inverter performance (better efficiency, reliability, lower cost, improved protection and monitoring features)
- More effective application, design and integration of PV systems
- Standardized interconnection requirements (IEEE 1547, IEEE 929, state requirements, etc.) for grid interactive systems
- Increased acceptance of Net Metering at individual utilities and by state and local governments

Because of the factors above and support by various government agencies, PV usage worldwide has grown roughly 15-40% for each of the past 10 years, while the inflation adjusted cost of PV energy has declined by roughly a factor of 10 over the past two decades and a factor of 2 over the past decade [1][2]. Today, PV energy costs about 20-40 cents per kilowatt-hour depending on the specific type of technology used, installation costs, and solar resource availability at the PV site. In 2004, for the first time ever, PV manufacturing will exceed or approach 1 GW of new modules, which puts PV about where wind power was a decade ago. PV growth is likely to continue unabated over the next decade on a trend similar to the recent experience with wind power. This paper will review some of the technical factors leading to the decline in the cost of PV systems and the robust growth of PV energy utilization, as well as make some predictions on future trends and technologies.

II. MODULE COSTS AND EFFICIENCY

The two most influential elements in the equation determining the cost of solar photovoltaic electricity are the price per peak Watt of PV modules, and the conversion efficiency of modules, expressed in W/m^2. The first is generally the dominant factor in the overall installed cost of systems, and it has been steadily declining for the past twenty-five years. Modules today can be purchased for prices as low as about $2.50 per peak watt under the best terms. Figure 1 shows the decline in average module prices over the past couple of decades (graph courtesy Terry Peterson, EPRI). Some factors that contributed to this decrease include reductions in the cost of PV cell grade silicon, manufacturing processes that waste less expensive silicon material, larger individual cell areas, thinner cells (wafer), increased scale of production, and general manufacturing improvements. While the price of modules is a key component of the system cost, it is important to recognize that it represents only about 25-50% of the installed system cost. Other elements

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include the balance of system components (inverters, mounting hardware, wiring and switchgear, and installation labor cost).

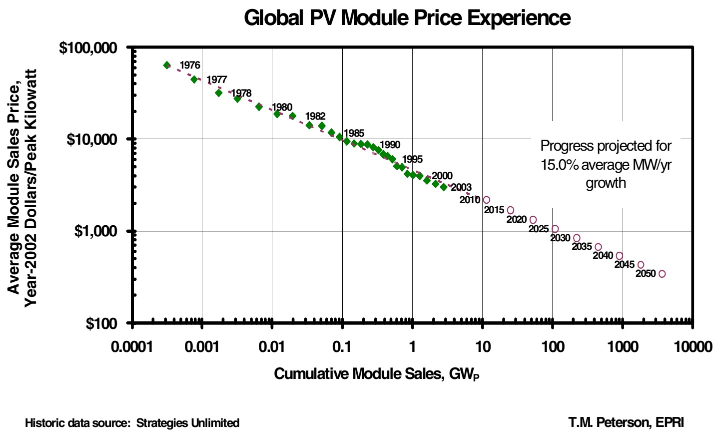

Figure 1 – Average Global PV Module Price since the Late 1970's through 2003. Data after 2003 is projected cost. (Graph Courtesy T.M Peterson, EPRI)

A second factor, module power density, affects the cost of the system through its impact on the installation labor and the remaining balance of system (BOS) costs. Higher cell efficiency (higher power density) results in less needed PV module area which reduces the cost of labor for installation, module shipping and handling costs, structural support costs, and inter-module wiring costs. New crystalline PV technologies that improve efficiency, among other things, eliminate the need for front-side metal grid lines and are achieving efficiencies approaching 20% on flat plate (non-concentrator) modules. Technologies that combine multiple layers of PV to absorb various portions of the spectrum also increase efficiency. As one example of a highly efficient product, Sanyo's HIT approach (this stands for *H*eterojunction with *I*ntrinsic *T*hin Layer) introduced in 1997 combines a crystalline PV cell with a thin Amorphous PV layer to achieve roughly a 16.1% module efficiency (see Figure 2).

Much work is underway in the industry to investigate and introduce a variety of alternative cell technologies to crystalline silicon. These include amorphous silicon technologies, Cadmium Telluride (CdTe), Copper Indium Selenide (CuInSe), polymer and organic based PV cells, and other PV cell technologies. Steady progress is being made in all of these areas, although flat plate single crystal and polycrystalline silicon cells are by far the dominating commercialized technology in use today. Concentrator PV systems with various types of cells (some having multilayered designs) are also being developed with some units having over 20% efficiency.

Figure 2 – Sanyo HIT 190 Watt PV Module Combines Crystalline and Amorphous Technologies to Create a 16.1% Efficient PV Module (photo courtesy Sanyo Solar)

Many of the higher efficiency flat plate solar module products in use today have improved efficiency by a factor of 1.2 to 1.5 compared to the best available commercial products of the early 1990's. Industry analysts predict that further improvements in cell efficiency will lead to many mainstream flat plate PV products with over 20% module efficiency (about 1.8 to 2 times the best products of a decade ago) by about 2010. There are even greater increases in efficiency that may be realized within a decade or two if multilayered cell technologies can be manufactured cost effectively. New materials that are being investigated, such as Indium Gallium Nitride (InGaN), potentially could increase module efficiency to a remarkable level beyond 50% [3]. These types of materials are currently at the very early research stages, so it is difficult to predict where they might lead us or when. Nonetheless, it is exciting to know that such high efficiency is not beyond the realm of possibility.

III. INVERTER TECHNOLOGY

The second most important area of development in the photovoltaic (PV) industry in the past few years is in the arena of inverter technology. There have been advances in reliability, efficiency, monitoring options, and cost and weight reduction. However, just as important as the evolution of product features, is the (relative) proliferation of tested and listed products in the marketplace (see the discussion later in this paper on UL1741). In the late nineties, for grid-paralleled inverters in the two to fifteen kilowatt range, there were no more than three manufacturers and four of five UL listed models available for the design engineer to choose from. Currently, there are ten or more manufacturers with over two dozen models in this range (examples include: Beacon Power, Magnetek, Fronius, SMA, Sharp, Xantrex, Solectria, PVPowered, Outback, and Vanner) and many others in the queue for testing and listing by nationally recognized testing labs. In the 20 to 500 kilowatt range there was only one company that manufactured listed inverters in the nineteen nineties. Today there are three that manufacture lines of listed inverters (SatCon, Xantrex, and Ballard) and even more options for jurisdictions that do not require listed devices. When compared with the variety of manufacturers and products in the variable speed drive industry (technologically a very closely related industry) this may seem a meager number; however it is a vast improvement over what was previously available to the designer.

Most modern grid tied inverters are currently based on pulse width modulated (PWM) transistor switching approaches that provide very low distortion waveform characteristics that satisfy IEEE 519-1992. This compares dramatically with many inverters of 10 or 20 years ago that were based on line commuted inverter topologies composed of silicon controlled rectifier (SCR) bridges that produced high levels of distortion and could not be operated to supply an independent island if desired (for UPS reliability purposes). The use of newer Insulated Gate Bipolar Transistors with higher switching frequency capability and lower losses than earlier transistor approaches has resulted in lower switching losses, less distortion and smaller filters with an overall reduction in inverter weight. Self commutated inverters also can operate at near unity power factor, a huge benefit for the utility system compared to earlier line commutated inverter designs that operate at 0.85 power factor or less.

The dc to ac conversion efficiency of nearly all modern inverter units exceeds 90% and many exceed even 95% at peak load. This compares favorably to earlier designs that many of which were well under 90% efficient. However, it is not just the higher efficiency that allows more power to be delivered from the solar array. Modern inverters also have very effective maximum power point tracking algorithms that squeeze out as much usable power as possible from the solar array by dynamically adjusting the dc bus voltage of the solar array to its optimum value as sunlight and temperature conditions vary. In addition, some new inverters permit multiple dc inputs with differing operating characteristics (maximum power currents and voltages). This feature gives greater latitude to the designer when faced with different physical spaces available for the PV arrays, such as on a residential roof. Figure 3 shows an example of a modern grid interactive inverter.

Figure 3 – Example of a Modern 5 kW Rated Single Phase Inverter (Unit Shown is Beacon Power M5. Photo courtesy Beacon Power)

IV. IMPROVED INSTALLATION APPROCHES

PV systems are being applied in ways that help reduce the cost of the system materials and installation labor. An example of continued development in the PV industry is in module mounting technology. Specifically, methods that allow simple, fast, laborsaving, wind-resistant, non-penetrating retrofits of existing building rooftops are essential for the rapid acceptance of PV. Again, in the early to late nineties there were only one or two companies and a small handful of products that offered solutions. Now there are seven or more companies offering a variety of products (PowerLight, SolarDock, SunLink, RWE, Evergreen, Uni-Solar, First Solar). Further, there has been more testing sponsored by federal and state agencies of wind loading, installation labor requirements, O & M burden, and other issues pertaining to mounting technology. These data are helping architects and engineers specify modules that can meet wind loading standards and are facilitating the safe and effective incorporation of PV modules into a wide variety of building designs.

In addition to the non-penetrating flat roof mounting technologies, advances have been made in pitched roof attachment methods, awning application and fixed-angle and tracking ground-mount technologies. These advances seek to reduce the cost of the BOS, while at the same time increasing the overall system efficiency. Despite their one-of-a-kind nature they have been able to receive the necessary listing from a nationally recognized testing laboratory in a time frame acceptable to tight construction schedules.

In the mid to late 1990's several approaches began to emerge where PV could be used in a manner that provides an offset of its cost by serving a multipurpose role [4]. These functions include:

- PV roofing panels that also serve as insulating panels
- PV awnings that provide a shading benefit
- PV roofing shingles
- PV power quality applications

In the first application, a good example is the PowerLight Corporation. They manufacturer a product that is composed of cement coated-interlocking polystyrene panels integrated with PV modules. These can be placed on a flat roof as a power producing element and the claimed R-19 insulation value adds considerable thermal insulation to any typical flat roof lowering air conditioning costs in the summer and heating costs in the winter. It also can lengthen the life of the roof (see Figure 4).

Figure 4 - Example of Interlocking Foam Insulating Panels Integrated with PV at Mauna Lani Bay Resort - Hawaii (Photo Courtesy of NREL and PowerLight Corporation)

In the second example, PV modules can be installed on the building façade or integrated into the façade to serve as a shading awning and power producing element. The PV awning concept has been demonstrated around the world with great success. A PV awning serves both the function of producing electricity as well as a shading function for the building windows. By keeping direct sunlight out, this helps reduce air-conditioning load in the summer. By selecting the appropriate awning position, it is possible to have good window shading performance in the summer while preserving the solar heat gain for the winter.

In the third example, the concept of a PV module that also serves as a roofing shingle product has been successfully commercialized. Here the benefit is that the PV modules themselves serve the dual function of a power producing element and also a waterproof shingle or roofing system. In this case the labor savings realized in not needing to install the conventional shingle as well as material cost savings offset of the avoided conventional shingle can slightly offset the effective cost of the PV installation. Figure 5 shows a typical PV roofing shingle system.

Figure 5 – Example of Amorphous PV Roofing Shingle (Photo credit: NREL)

In the final example, by including an Uninterruptible Power Supply (UPS) function as part of a PV system (a PV UPS), it is possible to improve power reliability at a site while *sharing* the inverter cost with that of the UPS. This can be achieved by use of a dual function inverter that provides dc to ac conversion for the PV array power as well as serving as the battery energy storage dc-ac converter for the UPS function. At sites where a conventional UPS is planned regardless of the decision to have PV, it is reasonable to assign essentially all of the inverter cost over to the UPS system. This translates into an effective cost reduction for the PV system capital cost of about 10-20%. Several companies have developed inverter products that provide this type of capability or a related, but less sophisticated, standby power capability. A dual function inverter of this kind is only marginally more expensive than a conventional inverter, but must have the appropriate integrated static switch and controls to transition seamlessly from solar PV mode to UPS mode if it is to provide true UPS capability.

Overall, these building integrated and dual role PV functions can serve to lower the "effective cost" of the PV energy. Building integrated PV is playing a leading role in many European PV applications and an increasing role here in the US. Reference 4 provides an estimation of the values achievable in dual use applications. These are generally in the range of 1-5 cents per kilowatt-hour and would have a cost offset value of roughly 5-25% of the PV energy cost depending on the situation (see Table 1).

Table 1 – Possible Value of Building Integrated PV and Multifunction PV Applications (adapted from Reference 4)

Type of Application	Reduction in "Effective Cost" of PV Energy (cents/kWh)
Building Integrated PV for Building Material Displacement	1-3
Integrated PV for shading/thermal benefit	2-5
T&D Support Applications	0-3
PV UPS approaches	1-3
Environment (typical green-customer willingness excluding value of government subsidies)	1-2

V. INTERCONNECTION STANDARDIZATION

A key issue positively impacting the PV industry is the recent development of "standardized" interconnection procedures by various states and the IEEE. Prior to these developments, the interconnection of small-scale PV systems was costly due to the customized interconnection approach required at each site. However, today, over 20 states have adopted specific interconnection methods for smaller DG and national standards now exist in the form of the IEEE 929-2000 (for PV) and IEEE 1547-2003 (for all DG) [5][6]. These documents define protection requirements for PV installations so that the installer and utility engineer have a ready resource available describing the required protection settings, grounding, and interface equipment. In addition to the IEEE standards, many state public service commissions have established their own interconnection procedures to streamline the process and reduce costs, while still preserving interconnection safety. Examples of states that have been leaders in developing standardized interconnection policies for small DG include New York, California, and Texas.

Standardized interconnection requirements make it possible for manufacturers to imbed within the PV inverter the needed protection functions for islanding and abnormal voltage-condition protection knowing that they will be accepted by the local utility. The acceptance by utilities that embedded relay functions within an inverter can work in lieu of the more expensive external "utility grade" relay packages has helped reduce the installation cost of smaller inverter based DG systems.

The development of active anti-islanding protection schemes has improved the robustness of inverter protection to the point where today there is less concern regarding islanding safety issues of smaller individual PV systems than there was 10 years ago. UL Standard 1741 for inverters has, amongst its other design requirements, a detailed anti-islanding test that inverters must pass if they are to be designated as non-islanding type inverters [7]. The IEEE standards and various state imposed standards rely upon the acceptance that a "UL type tested" non-islanding inverter per UL1741 will properly disengage from the line in the event of an abnormal utility system condition. The fact that a UL tested inverter can be installed and relied upon for protection under most circumstances has removed a great deal of cost and project uncertainty that might otherwise be incurred to prove that the anti-islanding protection scheme is appropriate.

The National Electrical Code (NEC) now has a fairly detailed explanation of the requirements for PV systems (NEC Article 690 – Solar Photovoltaic Systems). Article 690 describes the requirements of PV systems from the perspective of the customer side of the meter dealing with issues such as proper grounding (from a local perspective), the dc and ac side overcurrent and ground fault protection, and the general wiring arrangements that are appropriate from a local fire protection and safety perspective. The standard provides guidance for local electrical inspectors and PV installers to make sure that the systems meet the electrical code and do not pose a hazard.

Another area of state regulation related to interconnection that has helped PV is *Net Metering*. Today, over 33 states have net metering laws in effect. These allow PV systems and some other types of DG to export power at certain times and get the full retail rate credit for the value of the electricity rather than using a dual metered approach and receiving only the credit for the avoided cost of generation (avoided cost is usually only about 3 cents/kWh). These laws only generally apply to small renewable energy sites which over a long time have no net power export, but due to a mismatch between their local load and renewable generation periodically export power on a daily or seasonal basis.

While all of the codes, interconnection standards and net metering laws are still evolving from the perspective of how they are interpreted, and in supplemental sections that are still being written, what is already in place represents a big step forward in helping to implement PV in a more universally accepted lower cost approach. These standards are playing as much of a role in the market acceptance of PV energy as are the technology improvements discussed earlier.

VI. CONCLUDING COMMENTS

The PV industry is experiencing rapid growth due to improving technology, lower costs, government subsidies, standardized interconnection, and general public enthusiasm for an environmentally benign energy source. It is difficult to predict where PV will be in a decade or so because there are so many variables including market factors, political factors and technical factors that will impact PV growth. What is clear is that the current cost of PV energy (before subsidies) in many localities is in the range of about 20-40 cents per kilowatt-hour and that the lower end of this range is already beginning to compete directly with some of the highest price retail utility energy in the US. In fact, when subsidies are included, the effective cost is slightly lower than utility delivered power in several markets. As PV technology improves further, and the cost of PV energy moves down into the 12-30 cents/kWh range over the next 5-10 years, the lower end of this range will be competing strongly with utility supplied energy and a huge increase in grid connected applications is expected, especially at utilities with higher cost and in regions of higher solar resource.

We need to recognize that further improvements in the PV market are not just a factor of the PV module cost. Since PV modules can be purchased currently for only 2.5 to 6 dollars per watt, and since systems are being installed for 6-12 dollars per watt, clearly there are significant other balance-of-system factors that impact the total system cost. In fact, on a 30 year life cycle basis, inverter costs may contribute nearly as much as

PV module costs since they don't last as long as the modules and may need to be replaced 2-3 times over the 30 year lifecycle. As module costs have improved, there is pressure building to reduce the costs in the balance of the system components. Inverter suppliers need to reduce the prices of their products from the current typical $0.5-1.0 per watt to less than $0.25 per watt. PV installers need to find ways to reduce labor costs and/or gain added value either through use of more efficient lower area modules, or building integrated PV approaches that serve a dual function. These trends are occurring within the industry.

There is a temptation to compare future potential growth of PV to wind energy since PV seems to be on a development curve similar to wind power but about 10 years behind wind on a cost and capacity basis. While this appears to be true, there are some big differences between wind power and PV energy. First, wind has evolved mainly into a bulk power resource rather than a distributed generation resource – that is, wind turbines are installed in large wind farms that are on the order of 100 MW or larger and interconnected to the grid at the transmission system level. At this system level, wind must compete with bulk power market prices of 2-5 cents per kilowatt-hour. On the other hand, solar PV energy is more likely to remain a distributed generation resource connected in much smaller increments well under 1 MW at the distribution feeder or customer level. The retail value of electricity at this level is 6-20 cents per kilowatt-hour. Even though PV appears to be 10 years behind wind power on a cost basis, since it is competing in a higher price market, it actually is much closer to reaching a competitive cost point than is widely recognized. PV only needs to get to about 12 cents per kilowatt-hour to see huge market growth at current retail utility prices.

A final important point on the difference between wind and PV energy sources is that PV energy is much more compatible than wind energy with urban and suburban environments due to zoning restrictions and aesthetics. It is also more easily integrated into residential and commercial building designs. For these reasons, once market conditions are ready, PV is much more likely to see explosive growth in the mainstream consumer market than wind power ever will. However, the consumer market that PV is targeting is much less predictable than the bulk power market associated with wind power. The consumer market is as much driven by consumer preferences as it is by economics.

VI. Biographies

PHILIP BARKER (M'1986, SM'1999) received his BSEE and MSEE from Clarkson University, Potsdam, NY in 1985 and 1986 respectively and has 18 years experience working in the Electric Power Industry. He worked as a Consulting Engineer in distribution systems, lightning protection, distributed generation and power quality monitoring/analysis at Power Technologies, Inc. (PTI) for 14 years. At PTI he was responsible for many innovative projects related to photovoltaic energy and DG including the development of PV powered monitoring equipment, a 125 kW photovoltaic UPS system and several studies of PV T&D support analysis on distribution feeders. In 2000 Mr. Barker joined EPRI PEAC as the Engineering Manager for the Schenectady, NY branch office of that corporation where he was heavily involved distributed generation feasibility studies, power system impact studies and PV application studies. In 2003, Mr. Barker formed Nova Energy Specialists, LLC where he now works as its Principal Engineer. Nova is a consulting firm that provides the electric power industry with consultation on power distribution systems, distributed generation, and related R&D in the energy field. Mr. Barker has published 30 papers, is a Senior Member of the IEEE, and is active in various IEEE working groups related to distributed generation and power distribution systems.

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JAMES BING (M' 1987) James Bing is the founder and president of New Energy Options, Inc. He is a professional electrical engineer with registrations in Connecticut, Massachusetts and New York, working principally in data acquisition and power system design in the photovoltaic industry. In the past eight years Mr. Bing has collaborated on the design of numerous photovoltaic installations ranging in size from 200 kilowatts to a few hundred Watts. He has managed the installations and conducted inspections of systems in locations in the Caribbean, Mexico, the Philippines and throughout the United States. Prior to working in the photovoltaic industry Mr. Bing worked a for the R&D firm of Bolt Beranek and Newman in the area of sensor system and technology. In addition to his engineering credentials Mr. Bing also holds a Massachusetts Journeyman's electrician's license and possesses over twenty years of experience in the areas of electrical system design, project management, estimating, and personnel supervision in the electrical construction industry.

Mr. Bing holds a BS in Electrical Engineering from the University of Massachusetts at Lowell, as well as an AB in Anthropology from the University of California at Berkeley.

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REFERENCES

[1] Richard M. Swanson, "A Vision for Crystalline Solar Cells," Sunpower Corporation. Available at www.sunpowercorp.com as PDF
[2] Robert M. Margolis, "Photovoltaic Technology Experience Curves and Markets," Presentation at NCPV and Solar Program Review Meeting Denver Colorado, March 24, 2003, page 6.
[3] www.NewScientist.com, "Solar Cells Aiming for Full Spectrum Efficiency," December 8, 2002
[4] Philip P. Barker, Rick Lewandowski, "Enhancing the Economics of Photovoltaics through the Use of Advanced PV Technologies and High Value Applications," Presented at IEEE PES Summer Power Meeting, Chicago Illinois, July 21-25, 2002
[5] IEEE Standard 1547-2003, "Standard for Distributed Resources Interconnected with Electric Power Systems"
[6] IEEE Standard 929-2000, "Recommended Practice for Utility Interface of Photovoltaic (PV) Systems"
[7] UL 1741-2001 "Inverters, Converters, and Controllers for Use in Independent Power Systems"