AN EVALUATION OF INTEGRATED HIGH-CONCENTRATION PHOTOVOLTAICS FOR LARGE-SCALE GRID CONNECTED APPLICATIONS

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ABSTRACT

The purpose of this study was to determine the efficacy of a newly developed high-efficiency (greater than 18%), large-scale (20 kW) Integrated High-Concentration PV (IHCPV) system as a low cost power provider for utility grid-connected applications. High-concentration PV systems offer several cost advantages for large (multi-megawatt) applications. By concentrating sunlight with low cost plastic Fresnel lenses, they reduce the amount of costly silicon cell material required to generate a given amount of electricity by an amount approximately equal to the concentration ratio, in this case 300X. The novel 20 kW IHCPV system was installed at two major utilities: Arizona Public Service's Solar Test and Research (STAR) facility and the Photovoltaics for Utility Scale Application (PVUSA) facility. This innovative design further reduces costs by "integrating" the concentrating optics and the receiver plates with the tracking structure thus eliminating inefficient modular construction. Many studies have shown that once PV costs are reduced to below $2.00/watt, entry into the utility market will accelerate. The IHCPV system is considered to be the leading candidate to meet this cost threshold in the near term. This paper reports on the performance of the IHCPV systems and offers an analysis of the economics of HCPV systems for utility-scale applications.

BACKGROUND AND EXPLANATION

To date, available information regarding the utilization of high-concentration (>250X) photovoltaic systems has been largely based on theoretical data and analysis. This has resulted in some strongly held perceptions regarding the viability of the technology in large-scale utility installations. This paper attempts to examine some of these perceptions and demonstrate the underlying reality based on the results of actual fielded installations.

A uniquely structured, integrated, high-concentration (260X) photovoltaic (IHCPV) system has been developed for cost-effective, utility-scale applications. The first prototype 20 kW array was deployed at Arizona Public Service's Solar Test and Research (STAR) facility in Tempe, AZ in October, 1994. A second prototype system was installed at the PVUSA facility in Davis, CA in September 1995 as part of the Emerging Technical Program (EMT-3). A second "Pre-Production" 20 kW system has just been completed at the STAR site.

High-concentration PV systems offer several distinct advantages for low cost power generation: (1) cost reduction through the optimum utilization of silicon (concentrator systems reduce the amount of costly silicon required to generate a given amount of electricity by an amount approximately equal to the concentration ratio), (2) higher conversion cell efficiency at concentration vs. one-sun, and (3) inherently higher capacity factor (compared to fixed-tilt, flat-plate systems) in high direct normal insolation (DNI) areas because of its built-in tracking. Despite these inherent cost reducing elements, high-concentration PV systems have not previously emerged for large-scale utility use because of: (1) the lack of a stable, high performance, commercially available high-concentration solar cell, and (2) the high costs associated with the PV modules, structure, tracking system, and ancillary equipment.

The development of the AMONIX HCPV solar cell paved the way for commercial deployment of HCPV systems [1]. This cell has achieved a world record for commercially manufactured concentration cells: >26% efficiency at ≈ 300 X concentration, 25^0 C.

With the arrival of a stable high performance cell, high-concentration PV systems can now be realized. However to reduce costs, considerable effort has been applied so that all of the savings resulting from greatly reduced silicon usage does not get lost in the cost for the structure, tracker, and ancillary equipment required in concentrating systems. The result is the Integrated High-Concentration PV (IHCPV) array. The new, innovative

Presented at the 25th IEEE Photovoltaic Specialists Conference, May 1996, Washington, D.C.

(patented) IHCPV system concept eliminates much of the costly hardware used in earlier high-concentration designs. This has been accomplished by the simplification of the array structure which (1) eliminated earlier separate "box"-type modules mounted on structure assemblies, and substitutes an integrated design which combines both the load-bearing structure and the Fresnel lens/receiver plate elements thus eliminating the need for separate modules, and (2) a novel, manufacturing-worthy receiver plate which makes use of "circuit-board" construction techniques eliminating costly and labor intensive cell packaging and interconnects. A schematic illustration of the IHCPV system is shown in Figure 1. Figure 1 (a) shows a picture of the system at Arizona.

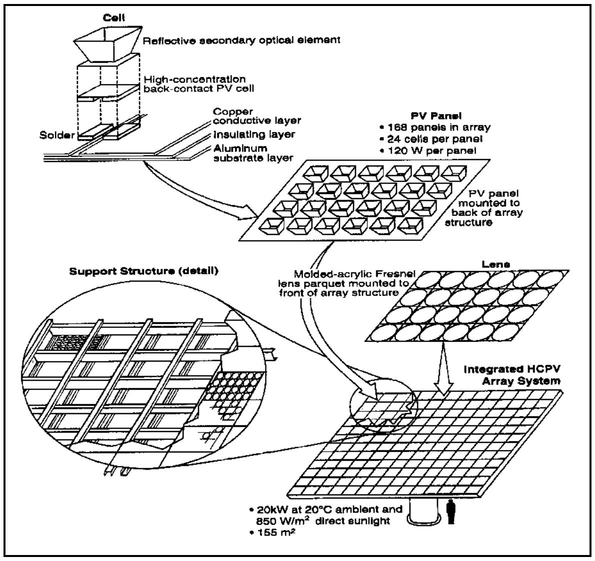

Figure1: Schematic of the IHCPV System

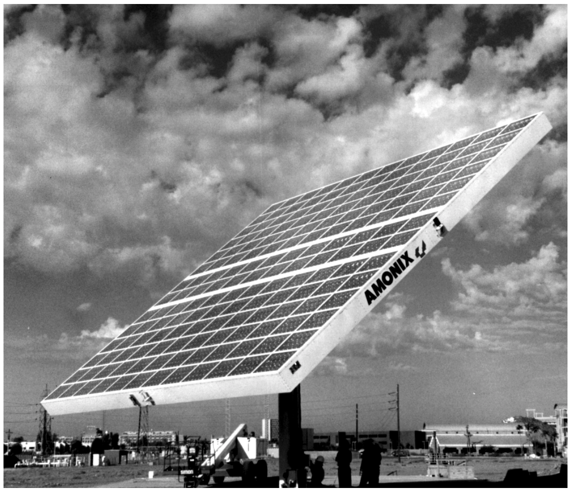

Figure 1(a): Photograph of IHCPV System at STAR

EVALUATION FOCUS

Among the perceptions that have grown up around HCPV are that: (a) HCPV doesn't work to its theoretical promise of high performance, (b) that it is too complex, (c) that its cells operate at relatively high temperature and that it is too susceptible to the effects of high cell temperature on performance, and that (d) manufacturing and operational costs are too high.

(a) HCPV Performance

The systems deployed at STAR and PVUSA have demonstrated that the ICHVP technology has the highest sunlight to electricity performance of any commercial PV system by a wide margin (Figure 2). Both the original and Pre-Production STAR systems developed conversion efficiencies greater than 18%. This 40% average increase in performance, coupled with increased capacity factor, clearly shows the energy production potential of HCPV compared to competing commercially available PV technologies.

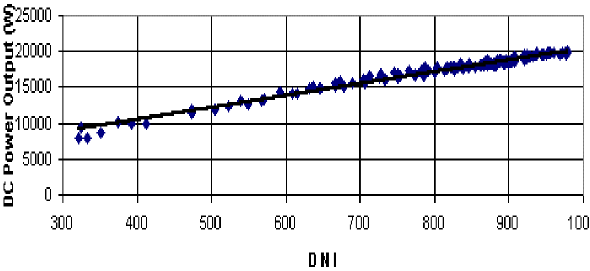

Figure 2: IHCPV Output Power vs Direct Normal Insolation

(b) HCPV Complexity

Because HCPV must actively track the Sun, questions arose regarding the added complexity of achieving accurate tracking. Figure 3 shows normalized efficiency (in kW at PVUSA test conditions) versus angular offset. Note that an angular misalignment of .3^0 results in a loss of 5% and a misalignment of .5^0 results in a loss of 10%. Misalignment of $\pm.2^0$ (the actual fielded results) show negligible loss. While great care must be given to tracking alignment during the design stage, practical experience indicates that misalignment less than $\pm .2^0$ is readily attainable.

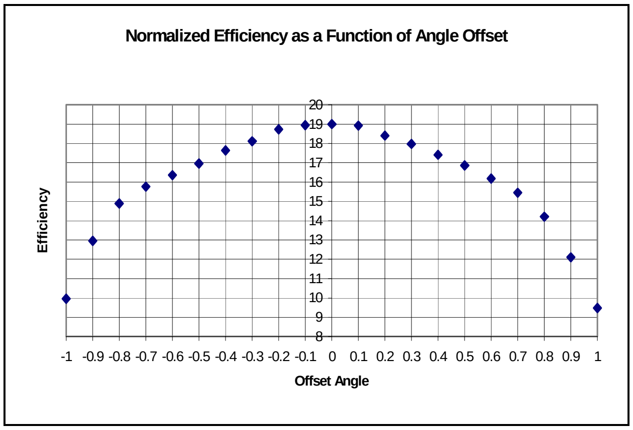

Figure 3: Normalized Efficiency as a Function of Offset Angle

(c) HCPV Cell Temperature Effects

The temperature sensitivity of the IHCPV system's output power is much lower than flat-plate systems (approximately 35~40%). The de-rating factor for flat-plate systems with increasing temperature is approximately $0.4\%/^0$C and that of the IHCPV system is $0.25\%/^0$C. This reduced sensitivity is due to the physics of the semiconductor. The temperature sensitivity of open circuit voltage (Voc) is mainly dependent on the voltage difference between the bandgap of the material and actual Voc (one-Sun cell Voc ≈ 600 mV; HCPV Voc ≈ 820 mV; Silicon bandgap ≈1.1 eV) [2].

In addition to the lower sensitivity, the IHCPV system has a structural advantage for better convective heat transfer due to the pedestal mount and individual cell cooling using large area heatsinks (fins). As a result, the IHCPV system's output power is more stable with temperature.

(d) HCPV Manufacturing and Operational Costs

The technical challenge of designing a low cost HCPV system have been met with the integrated design concept. All of the system elements (lens, receiver plate, tracking structure) have been planned for high volume cost effective manufacturing methods. Detailed manufacturing cost analysis by Amonix and the Electric Power Research Institute conclude that IHCPV is a leading candidate to meet the utilities cost goal of <$2.00 per installed watt. Additionally, IHCPV is the only technology able to reach this cost goal within 2-3 years without the requirement of building specialized manufacturing facilities.

Operational costs for HCPV represent approximately $11K/MW/year [3]. These costs are more than offset by the increased energy production of HCPV (see Figure2). Of particular note is the requirement to keep lens soiling to a minimum. Experience in the desert Southwest (STAR) as well as in a Northern California agricultural area (PVUSA) indicate that for optimum performance the HCPV lenses must be washed on a weekly basis assuming no rain.

At Phoenix, Arizona, based on calculations, a 2-axis tracking IHCPV would be anticipated to produce about 23% more energy than a single crystal silicon flat-plate system facing South, fixed at the appropriate latitude angle [4]. Figure 4 is based on actual power and insolation data for two such systems as recorded on May 6, 1996 a the Arizona Public Service STAR Facility in Tempe, Arizona. The data for the IHCPV array is actual DC power while the actual DC power output for the flat plate array was scaled up by a factor of 9.83 (the flat plate system is rated at 2.096 kW) to reflect similar peak power ratings at Standard Test Condition (20.6 kW at 850 W/m^2 DNI for concentrators, 1,000 W/m^2 insolation for flat plate and both at 25^0 C cell temperature). Both arrays were soiled from dust and obviously exposed to the same ambient temperature which was near 38^0 C. Note that, for the same nameplate rating, the IHCPV array produces **35-40%** more energy overall especially in the early morning and late afternoon.

CONCLUSION

Due to the lack of actual field experience, many misperceptions exist about high-concentration PV systems. Some of these misperceptions are that: (a) HCPV doesn't work to its theoretical promise of high performance, (b) that it is too complex, (c) that its cells operate at relatively high temperature and that it is too susceptible to the effects of high cell temperature on performance, and that (d) manufacturing and operational costs are too high.

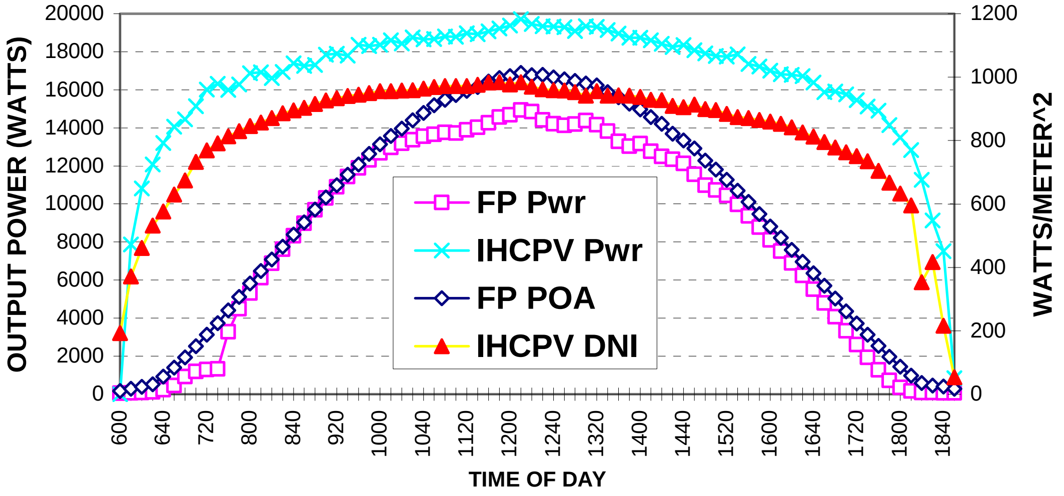

Figure4: Comparison of Energy Production for Flat-Plate and IHCPV Systems

Information garnered over the last two years and based on full-scale (20 kW) IHCPV system deployment disprove these misperceptions. IHCPV has proven itself to have superior performance (18% sunlight to electricity conversion efficiency) compared to competing PV technologies. The integrated concept greatly simplified previously complex system design. Operating cell temperature is not a problem due to both superior passive cooling as well as the lower de-rating factor for concentrator cells. Manufacturing costs are expected to reach the utility's cost goal of <$2.00 per installed watt within 2-3 years (ahead of competing technologies) and operational costs are negligible.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of Dr. Peter Johnston, Mr. Herb Hayden, and Mr. Pete Eckert of Arizona Public Service's STAR facility, Mr. Bob Hammond of Arizona State University, Mr. Brian Farmer of PG&E/PVUSA, Mr. Tony Reyes and Mr. Paul Hutchinson of Endicon/PVUSA, Dr. Edgar DeMeo of the Electric Power Research Institute. With the support of these people, and many others, the success of the IHCPV program was greatly accelerated.

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