A NOVEL HIGH-CONCENTRATION PV TECHNOLOGY FOR COST COMPETITIVE UTILITY BULK POWER GENERATION

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ABSTRACT

This paper describes an innovative design for a nominal 20 kW, integrated, high-concentration (260X) photovoltaic (IHCPV) system which has been developed for cost-effective, utility-scale bulk power generation. This technology recently set a new world record for efficiency : 20.3% under STC (18.5%, >20 kW at PVUSA operating conditions). High-concentration PV systems offer several advantages for low cost power generation: (1) cost reduction through the optimum utilization of silicon, (2) higher conversion cell (hence system) efficiency at concentration vs. one-sun, and (3) inherently higher capacity factor in high direct normal insolation areas because of its built-in tracking. Previously little progress has been made in deploying HCPV for large-scale electricity generation because of: (1) the lack of a stable, high performance, high-concentration solar cell, and (2) the high cost associated with the PV modules, structure, tracking system, and ancillary equipment. With the arrival of a stable high performance cell developed by AMONIX, high-concentration PV systems can now be realized. A novel integrated system concept greatly reduces the costs associated with system hardware and labor by; (1) integrating the load bearing structure and the Fresnel lens/receiver plate elements eliminating the need for separate modules, and (2) use of a manufacturing-worthy receiver plate which makes use of “circuit-board” construction techniques. A full-scale 20 kilowatt IHCPV system has been deployed, and test results which validate the system design are reported. The IHCPV system development is complete and only volume production, **not technical breakthroughs**, is needed to meet the cost goals of <$2.00/watt at multi-megawatt levels.

INTRODUCTION

This paper describes a uniquely structured, integrated, high-concentration (260X) photovoltaic (IHCPV) system which has been developed for cost-effective, utility-scale applications. A 20 kW array, based on PVUSA operating conditions, was deployed at Arizona Public Service’s Solar Test and Research (STAR) facility in Tempe, AZ in October, 1994 (see Figure 1).

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.

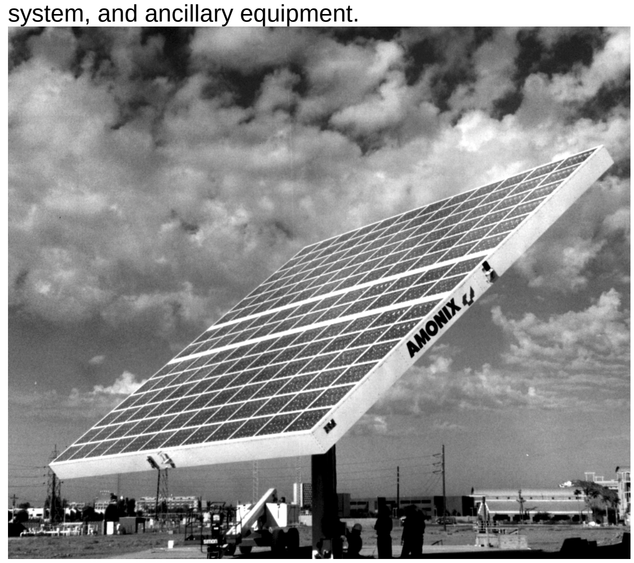

Figure 1: 20 kW IHCPV System

The development of the AMONIX HCPV solar cell has 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 850 DNI, 25^0 C. AMONIX has used the unique approach of utilizing commercial Integrated Circuit foundries for cell production rather than expending the time and capital required to build specialized facilities around this unique technology. This approach results in immediate access to volume cell production capacity along with predictable costs.

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 (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 (Figure 2), 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 (Figure 3), 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. Figure 2 shows a first generation HCPV system and Figure 3 shows the vastly simplified IHCPV design.

The IHCPV system completed electrical and mechanical design qualification to the Department of Energy’s Sandia National Laboratories specification in the Fall of 1993. This 2,000 watt testbed system subsequently set a new world record for electrical PV energy conversion efficiency at greater than 20%.

The first full-scale 20,000 watt system has been deployed at Arizona Public Service’s STAR facility (see Figure 1). Performance of this system is discussed below.

INTEGRATED ARRAY DESCRIPTION

The AMONIX IHCPV system utilizes a Fresnel lens of 260X geometric concentration ratio to focus sunlight onto back-junction, point-contact photovoltaic cells specifically designed to handle the high solar flux. The cells must be precisely positioned relative to the lens and the assembly must track the sun accurately in order to utilize the direct normal insolation. Tracking tolerance is improved by adding secondary optical elements to redirect any light that might otherwise miss the cell. The conventional method for constructing concentrator PV systems has been to build weather-tight modules (boxes) which support Fresnel lens parquets, individually mounted PV cells, secondary optical elements and associated electrical circuitry; to mount these modules onto a two-axis tracking structure; and, to electrically connect the modules to form an array (see Figure 2). Since concentrators usually have long focal distances, modules are typically bulky and can be difficult to handle and expensive to ship. Installation of modules onto trackers requires an alignment procedure to account for structural imperfections and insure that all modules are aimed in the same direction.

The basic concept of an "integrated array" is to integrate the module housing or module structure into the tracker structure thereby eliminating redundant structural components. The integrated structure was designed by Scientific Engineering, Inc. who is teamed with AMONIX for the commercialization of IHCPV technology. As shown by Figure 3, Fresnel lens parquets attach directly to the top of the tracker structure and PV "panels" or "circuit boards" attach directly to the back of the structure. The concept requires that components be precisely fabricated and assembled in order to meet optical alignment requirements and that the structure have sufficient stiffness to maintain module alignment under all operating conditions. The concept also requires that water sealing be incorporated into the design to prevent electrical shorting.

The lens parquets and PV panels are the same physical size, based upon a 4x6 matrix of cells. The acrylic lens parquet is made using automated compression molding technology. The lenses are manufactured by Fresnel Optics, Inc., another member of AMONIX’s commercialization team.

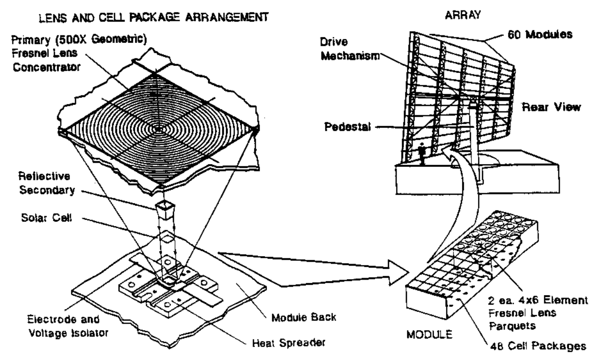

Figure 2: Early HCPV System Design (with modules)

The substrate for the PV panel as illustrated in Figure 3 consists of a three part thermally conductive laminate, with the front surface being electrically conductive and electrically isolated from the back surface. The cells, reflective secondary optical elements, blocking diodes, and inter-panel wiring terminations are all soldered directly to the top surface of the laminate thereby eliminating cell packages. The electrically conductive PV panel surface is also configured to match the mounting pattern of the AMONIX HCPV cell as well as provide the necessary circuitry for series and parallel cell connections (i.e.-no cell to cell wiring). The precise placement of components on the laminate and the subsequent soldering operation can be accomplished with robotics and other common automated manufacturing techniques. Shipments of lens parquets and PV panels are much more compact than assembled module boxes.

A 20 kW IHCPV array consists of 168 Fresnel lens parquets and PV receiver plates mounted to a tracking structure. Each Fresnel parquet has an aperture area of 0.7587 m^2 for a total array aperture area of 127.46 m^2. The overall tracking structure is 159 m^2 and is attached to a center pedestal via a two-axis mechanical drive. The tracker is designed to operate in winds up to 35 MPH and to survive winds up to 90 MPH in a stowed position.

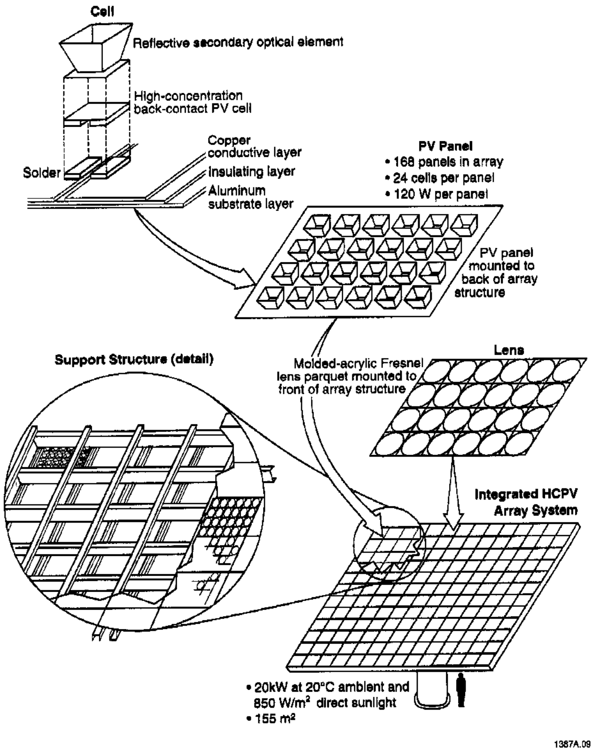

Figure 3: The Integrated High-Concentration PV Concept

The integrated tracking structure (designed and installed by Scientific Engineering, Inc.) is 13.81 m by 11.53 m and consists of a matrix of identical structural steel "cees" and "hats", two "backbone" trusses and a drive interface structure. The cees and hats are fabricated using automated roll-forming and numerical punching technology. Roll-forming allows cost effective customization of the cross-sectional shapes of the structural members such that members can be designed to fit within the available "non-optical areas" thereby keeping the gross array area as small as possible and allowing for optimization in terms of member strength and weight. Fastening holes will ultimately be numerically punched in all members in order to maintain the required precision for alignment. This structural concept eliminates material waste, minimizes fabrication labor and field assembly labor, eliminates the need for welding or painting since galvanized material can be used, and, due to the precision of fabrication, eliminates the need for manual alignment adjustments in the field.

The low cost two-axis utilizes a planocentric ring drive for azimuth rotation with a gear ratio of 31,102:1 and a jackscrew arrangement with a gear ratio of 31,640:1 for elevation rotation. The drive can rotate the array in azimuth plus or minus 180 degrees from south, and 90 degrees in elevation. Tracking control is accomplished with a time based, open loop control system. A microprocessor computes the position of the sun and directs the tracker accordingly. The tracker keeps track of its current position by use of a Hall-Effect encoder on the motor shaft of the azimuth and elevation drives. By counting motor revolutions from a known reference position and given the drive parameters, the control system can align the tracker with the sun to within 0.05 degree accuracy.

Electrically, the 168 Fresnel lens parquets and mating PV receiver plates are subdivided into three subarrays. Each subarray consist of two parallel strings of 28 receiver plates in-series for a nominal rating of 32 amperes at 210 V_{DC}. Each subarray is connected to one phase of a three phase, grid interactive inverter which has a 480 VAC, 60 Hz, three phase delta output. Each of the three phases of the inverter are controlled independently. Once connected to the utility grid, each control circuit allows sufficient current to be delivered to the utility to bring the array to its maximum power point.

SYSTEM PERFORMANCE

Flatness measurements were made on the structure to determine the amount of gravity sag and to validate finite element model predictions. The results of these measurements indicate that misalignment due to gravity sag is less than 0.1 degree and that the model predictions were reasonable.

Two sets of tracking error monitors are installed on the tracker and are used to measure tracking accuracy. The results of these measurements indicate that the system is capable of tracking the sun to within 0.1 degree accuracy throughout the day.

Each PV receiver plate was individually tested at the factory and ranked according to peak power performance. The plates were positioned in the array so as to minimize power losses due to mismatch. Mismatch losses for the overall array are less than 1%. Wiring loses within the array and between the array and inverter are less than 1%

Thermocouples are used to measure various temperatures during the operation of the array, including ambient air temperature. In order to measure variations in temperature, thermocouples were placed on one plate on the lower part of the array and one plate on the upper part of the array. For each plate, one thermocouple was placed immediately behind a cell, one thermocouple was placed immediately between two cells and one was placed in the air just above the inside of each plate. The results of the temperature data suggest that the top plates operate about 5^{o} C higher than the bottom plates.

The electrical performance of each subarray is monitored by measuring current and voltage simultaneously with direct normal insolation. Readings are recorded every minute and averaged over a ten minute period. Power from each subarray is then computed and summed for the total array. Given the aperture area and the above measurements, operating efficiency is then computed. Figure 4 depicts actual data of output power (DC) versus DNI under variable temperature conditions. Note that the array has exceeded the design goal of 20,000 watts.

SUMMARY

A novel, cost-effective, high-concentration PV system has been designed and a 20 kW array has been deployed. Test results validate the high performance capability of the IHCPV system. A new world record for system efficiency has been achieved: 20.3% under STC (18.5% at PVUSA operating conditions) [2]. This performance, combined with the cost-effective integrated design make IHCPV a leading contender for low-cost utility-scale bulk power generation. **No technical breakthroughs (only volume production and deployment) are needed to reduce the cost to <$2.00/W at multi-megawatt levels.**

ACKNOWLEDGMENTS

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The authors wish to recognize Arizona Public Service for their leadership in the commercial deployment of the IHCPV technology. In particular, we wish to acknowledge the support of Dr. Peter Johnston, Mr. Herb Hayden, and Mr. Peter Eckert.

REFERENCES

[1] S. Yoon, V. Garboushian, “Commercialization of High-Concentration Back-Junction Point-Contact Photovoltaic Cells; Successful Pilot Production”, *Proc. of 11th E.C. Photovoltaic Solar Energy Conference*, 1992, pp. 257-260

[2] **Standard Test Conditions**
1000 W/m^2 direct normal irradiance, 25^0 C **cell temperature**, and 3 m/s wind speed (at 10 meters above grade)
PVUSA Test Conditions for Concentrators
850 W/m^2 direct normal irradiance, 20^0 C **ambient temperature**, and 1 m/s wind speed (at 10 meters above grade)

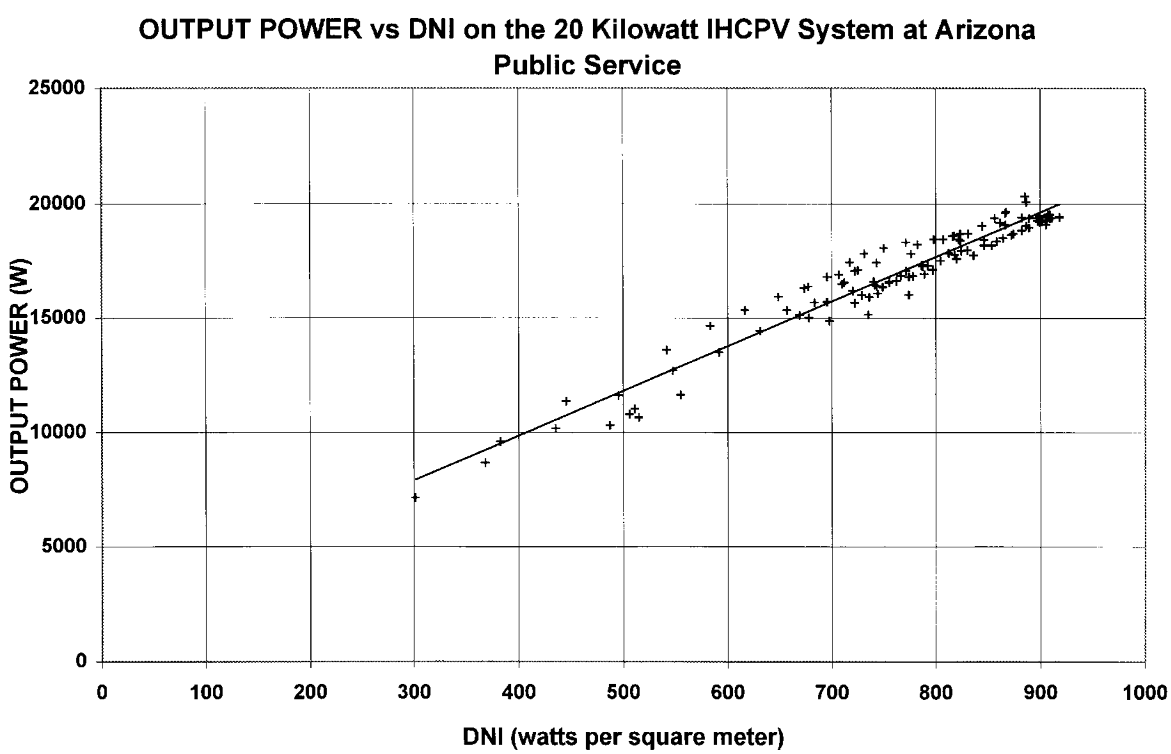

Figure 4: Data from AMONIX 20 kW IHCPV System at Arizona Public Service