

PROGRESS IN PHOTOVOLTAIC COMPONENTS AND SYSTEMS

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ABSTRACT: The Photovoltaic Manufacturing Research and Development project is a government/industry partnership between the U.S. Department of Energy and members of the U.S. photovoltaic (PV) industry. The purpose of the project is to work with industry to improve manufacturing processes, reduce manufacturing costs, and improve the performance of PV products. This project is conducted through phased solicitations with industry participants selected through a competitive evaluation process. Starting in 1995, the two most recent solicitations include manufacturing improvements for balance-of-system (BOS) components, energy storage, and PV system design improvements. This paper surveys the work accomplished since that time, as well as BOS work currently in progress in the PV Manufacturing R&D project to identify areas of continued interest and product trends. Industry participants continue to work to improve inverters and to expand the features and capabilities of this key component. The industry also continues to advance fully integrated systems that meet standards for performance and safety. All participants included manufacturing improvements to reduce costs and improve reliability. Accomplishments of the project's participants are summarized to illustrate the product and manufacturing trends.

Keywords: Inverter- 1: Balance of Systems- 2: Components- 3

1. INTRODUCTION

The Photovoltaic (PV) Manufacturing Research and Development (R&D) project is a government/industry partnership between the United States (through the U.S. Department of Energy [U.S. DOE]) and members of the U.S. PV industry. The purpose of the project is to work with industry to improve manufacturing processes, reduce manufacturing costs, and improve the performance of PV products. This project is conducted through phased solicitations with industry participants selected through a competitive evaluation process. Since the project was implemented during 1991, there have been five solicitations for R&D on manufacturing process problems. Starting with the fourth solicitation in 1995, the topics were expanded to include manufacturing improvements for balance-of-system (BOS) components, storage, and system design improvements. These topics are included in the fifth solicitation initiated in 1998, and this work is now in progress. Accomplishments in the area of PV module manufacturing resulting from the PV Manufacturing R&D project are described in other publications [1,2]. This paper reviews specific progress and trends in PV systems and components.

2.0 TRENDS IN PV COMPONENT ADVANCES

Work in the area of BOS and PV systems has been in progress under the PV Manufacturing R&D project since 1995 [3]. These advancements and trends are illustrated by the work of the various participants in the Manufacturing R&D project and are described in the following sections. All project participants included manufacturing improvements to reduce costs and improve reliability as a part of their overall effort. A survey of the work accomplished over this

period illustrates areas of particular interest to industry and indicates general trends in product improvements. These accomplishments are described in the following sections.

2.1 Trends in Completed Projects

Thirteen awards were made in 1995. Of these 13, 8 awards were in BOS and system-related topics. Of these 8, three worked specifically to improve inverters, three addressed both power conditioning and integrated PV systems, and two worked on approaches to integrate systems and PV system manufacturing improvements. The following sections describe this progress, with participants grouped generally by topic. The participants and the focus of their work are listed in Table I.

2.1.1 Inverters

Three companies worked specifically to improve inverters. These three illustrate the trend for inverters to provide additional features in addition to basic power conversion. Companies working in this area used advanced electronics, new approaches to power bridge design, and complex software to improve performance, reduce costs, and provide monitoring and improved communications options. In alphabetical order, the first company described in this group is *Advanced Energy, Inc.*, which designed a hybrid inverter to interface with PV, diesel, and wind power sources. Advancements demonstrated by a 60-kW prototype included digital control, optimized magnetics, and smart-power components. Advanced Energy also included a communications interface. The second company in this group, *Omnion Power Engineering Corporation* (now a division of S&C Electric Company), improved their 100-kW inverter, implementing a highly integrated power-switching bridge, air-core transformers, and condensed printed-circuit boards (PCB). Omnion reports labor is reduced by half,

Table 1: List of participants and work in PV Manufacturing R&D components and systems completed in 1998.

Company or Team	R&D	Inverters (Power Conversion Systems)	Advanced Components & Integrated Systems	Manufacturing and System Integration
• Advanced Energy, Inc.	Hybrid inverter	X		
• Omnion Power Engineering, Inc.	Advanced grid-tied inverter	X		
• Trace Engineering	Modular inverter	X		
• Ascension Technology, Inc., with ASE Americas, Inc.	Module-scale inverter & integrated PV product	X	X	
• Solar Design Associates, with BP Solarex & Advanced Energy, Inc.	Integrated PV array mounting, module-scale inverter	X	X	
• Utility Power Group, Inc.	Grid-tied PV system	X	X	
• Evergreen Solar, Inc.	Alternative encapsulants, new module mounting approaches			X
• Solar Electric Specialties, Inc.	Integrated PV products			X

and manufacturing costs and parts count are reduced to one-third that required for their earlier model [4]. The final company included in this group, *Trace Engineering*, developed a modular, bi-directional, 2.5-kW Series PS2 inverter designed for mass production. The PS2 is capable of grid-tied operation, or stand-alone with a battery, and can function in parallel with other inverters through a Sinewave Inverter Paralleling kit. Trace reports the PS2 has 35% fewer parts, is 40% smaller, and requires 42% less assembly labor than their previous SW series units [5].

2.1.2 Advanced Components and Integrated Systems

Three companies focused on power conversion improvements and PV product integration. *Ascension Technology, Inc.* (now a division of Applied Power Corp., or APC/AT), designed and completed pilot manufacturing of the SunSine™ 300 AC PV Module. This fully-integrated PV product incorporates their module-scale, 250-Wac SunSine™ 300 inverter attached to the back of the ASE Americas, Inc., large-area PV laminate (260 to 300 Wdc). The SunSine™300 inverter includes passive and active anti-islanding protection and maximum-power-point tracking [6]. *Solar Design Associates, Inc.*, led a team with Advanced Energy and BP Solarex to address several aspects of PV systems [7]. Advanced Energy enhanced their 250-Wac module-scale inverter to include software controls, and BP Solarex developed a low-cost, pre-engineered assembly that is now part of their pre-packaged Millennia® PV arrays. This assembly integrates module framing, mounting, array wiring, grounding, and lightning protection. The third company in this group, *Utility Power Group, Inc. (UPG)*, established a manufacturing process for integrating PV laminates into modular panels that are pre-assembled into subarrays and installed in array strings of up to 15 kW each [8]. An Integrated Power Processing Unit (IPPU) manages single-axis tracking and power conversion for each string. The factory-assembled IPPU combines all the necessary power conversion/control electronics, array-tracking control

electronics, source-circuit protection hardware, and DC and AC switchgear for utility applications.

2.1.3 PV System Manufacturing Advancements

Two participants completed manufacturing and product advancements for fully-integrated systems. *Evergreen Solar, Inc.*, completed several manufacturing improvements, including the development of an air-cured transparent encapsulant for manufacturing PV modules using a continuous, non-vacuum lamination process. The company also identified a PV-laminate backskin material. The unique properties of the backskin resulted in a mounting system design for rapid panel installation in the field [9]. *Solar Electric Specialties, Inc.* (now part of APC), developed two fully-integrated PV products to demonstrate the benefits of product integration, including lower costs for materials and labor and higher overall quality and reliability. Two product lines resulted from this work: 1) the Underwriters Laboratories (UL)-listed, stand-alone Modular Autonomous PV Power Supply consisting of PV modules and an enclosure containing solid-state power control and sealed batteries; and 2) the mobile Photogenset, which integrates a generator, PV array, and battery storage to provide off-grid AC power [10].

2.2 Trends in Projects Now in Progress

The trends of increased sophistication, improved manufacturing, and streamlined PV systems continue to be demonstrated in BOS subcontracts initiated during 1998 with the fifth solicitation. Work now in progress includes APC/AT, which has redesigned their module-scale inverter to improve performance, enhance reliability, and reduce costs. With these enhancements, the product is named the SunSine®. PowerLight Corporation has undertaken a broad range of product improvements and manufacturing steps with the goal of achieving a \$3.05/W_p installed cost for their PV system. Omnion is developing a sophisticated design for 1- and 2-kW grid-tied inverters. UPG is developing a

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Table II: The APC/AT SunSine™ demonstrates significant advancements over the original SunSine™ 300.

Item	Original SunSine™ 300	Revised SunSine®	Relative Improvement
Power rating	251 Wac	275 Wac	9.6%
Efficiency	87%	91%	4.7%
Communications	Signal	Infrared data link	Multi-functional

fully-integrated residential PV system that includes pre-packaged storage. As a group, these projects represent industry's continuing drive to reduce overall system costs and improve inverters. Details of this work are described in the following sections.

2.2.1 Manufacturing and Performance Improvements to the SunSine™ 300

The work now in progress by APC/AT follows the successful development of the SunSine™ 300. The advanced 275-Wac SunSine® incorporates significant operating enhancements, additional features, and streamlined manufacturing processes. Product improvements include a proprietary Zero Voltage Switching (ZVS) soft-switching approach and a modified transformer design to increase the unit's power and efficiency. Revisions to the PCB optimize performance and reduce overall size and costs. The PCB parts count has been reduced by 34%, non-standard parts are eliminated, and the board is redesigned for automated assembly. The SunSine® also has an infrared data link compatible with the IrDA™ interface used by PalmPilot™ and other electronic products. The SunSine™ advancements in performance and reduced costs as summarized in Table II.

2.2.2 Manufacturing Improvements for PowerGuard® PV System

The overall goal of PowerLight Corporation's work in this subcontract is to reduce costs. Their approach is to introduce incremental improvements to their PowerGuard® PV system components and automated manufacturing methods.

The PowerGuard® system is an approach that incorporates a proven roofing technique with PV. The system comprises electrically connected strings of PowerGuard® tiles, held in place, with no roof penetrations, by a ballasted curb (Figure 1). Over the past 18 months, PowerLight has designed an automated tile manufacturing facility and completed pilot manufacturing to demonstrate a capacity of 10 MW of PowerGuard® tiles/year. They have also reduced PowerGuard® tile production costs by 30% and reduced overall PowerGuard® system costs by 15%. The company is now refining automated processes to achieve production capacity of 16 MW per year. PowerLight also worked with lower-tier subcontractor Trace Technologies to modify their inverter to incorporate a data acquisition system and dial-up communication capability for audit-worthy verification of PV system performance. Trace also upgraded the design to digital circuitry and reduced total parts count by 25%.

2.2.3 Omnion Utility-Interactive Inverter

Omnion's objective is to produce 1- and 2-kW single-phase inverters for utility-interconnected applications. With modified design, the product's input voltage range will be 100 to 400 Vdc. The design will include provisions for optional or standard metering and data-acquisition connections, and interface and near-zero input voltage ripple due to active control to maximize array utilization. An inverter enclosure that meets UL requirements, and provides for a "plug together" inverter and base plate, will facilitate installation and service. Anti-islanding and ground-fault detection and protection are also planned.

2.2.4 UPG Integrated Residential PV System

UPG is completing development of a fully-integrated residential PV system that incorporates three distinct elements—a rooftop PV Array, a Power Unit, and an Energy Storage Unit. The modular PV Array comprises factory-assembled, modular subarrays, expandable to 4 kW, of either crystalline or thin-film PV modules. Trace Technologies is working as a lower-tier subcontractor to UPG to develop a Power Unit for this system. This bi-directional inverter supplies 120/240 Vac at 12 kVA continuous and 19 kVA of peak power, to manage battery charging, power-source switching (PV, utility, or battery), and utility interconnection. The unit's higher switching frequency increases power density, decreases the cost and weight of magnetic components, and increases conversion efficiency. The power-conversion topology also eliminates additional boost circuitry with its associated losses and expense. The modular Energy Storage Unit provides about 13 kWh of maintenance-free battery capacity. It interfaces with the Power Unit, communicating through a serial data bus. Each unit includes: 1) 32 valve-regulated lead-acid

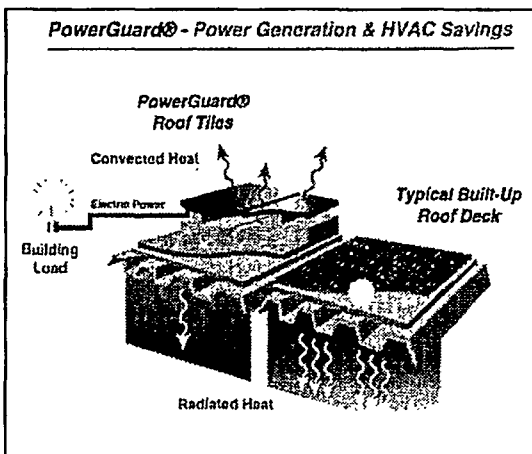


Figure 1: Schematic illustrating the structure of the PowerGuard® tile.

Table III: Advantages of Utility Power Group, Inc.. PV system compared to conventional residential rooftop PV systems.

Conventional Systems	Utility Power Group Residential System
Cost: \$US 5.75 – 7.50 per watt	Cost: \$US 4.75 – 5.50 per watt
Low inverter efficiency (85% – 93% at full power)	Efficiency 94% at full power
No integrated energy storage	Fully-integrated energy storage capacity (20 hour rate): 12.7 kWh

batteries, 2) overcharge protection circuitry for any given battery, and 3) a thermally insulated container with “smart” forced-convection cooling. The unit also incorporates software to monitor battery use. More units can be added if desired. The system improvements are compared to conventional systems and summarized in Table III.

3. CONCLUSIONS

The PV Manufacturing project has conducted R&D with industry in the area of BOS and systems since 1995. During that time, industry has demonstrated continued improvements in a broad range of inverter designs. These improvements have emphasized sophisticated power electronics, software, and other design improvements to enhance the capabilities of the inverters, as well as to reduce costs and simplify manufacture. Industry also continues to work toward integrated PV systems to reduce overall installed costs and to meet a variety of applications for PV products. These trends are expected to continue as new electronic sub-components become available and public demand for integrated systems continues to expand.

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