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# PROGRESS IN PHOTOVOLTAIC SYSTEM AND COMPONENT IMPROVEMENTS

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ABSTRACT: The Photovoltaic Manufacturing Technology (PVMaT) project is a partnership between the U.S. government (through the U.S. Department of Energy [DOE]) and the PV industry. Part of its purpose is to conduct manufacturing technology research and

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development to address the issues and opportunities identified by industry to advance photovoltaic (PV) systems and components. The project was initiated in 1990 and has been conducted in several phases to support the evolution of PV industrial manufacturing technology. Early phases of the project stressed PV module manufacturing. Starting with Phase 4A and continuing in Phase 5A, the goals were broadened to include improvement of component efficiency, energy storage and manufacturing and system or component integration to bring together all elements for a PV product. This paper summarizes PV manufacturers' accomplishments in components, system integration, and alternative manufacturing methods. Their approaches have resulted in improved hardware and PV system performance, better system compatibility, and new system capabilities. Results include new products such as Underwriters Laboratories (UL)-listed AC PV modules, modular inverters, and advanced inverter designs that use readily available and standard components. Work planned in Phase 5A1 includes integrated residential and commercial roof-top systems, PV systems with energy storage, and 300-Wac to 4-kWac inverters.

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

## INTRODUCTION

The DOE initiated the PVMaT project in 1990 to assist the U.S. PV industry to extend its world leadership role in PV manufacturing and the commercial development of PV modules and systems. The PVMaT project is a government/industry R&D partnership between the U.S. federal government (through the DOE) and members of the U.S. PV industry. PVMaT is designed to assist industry to improve manufacturing processes, accelerate manufacturing cost reductions for PV modules, improve commercial product performance, and lay the groundwork for a substantial scale-up in the capacity of U.S.-based PV manufacturing plants.

The PVMaT project is being conducted in phases 1, 2, 3A, 4A and 5A, designed to address selected R&D topics. A description of the focus and accomplishments for phases 1-3A and an introduction to 4A have been detailed in previous papers [1-4]. Phase 4A, Product-Driven manufacturing, was divided into two parts, 4A1 - Product Driven System and Component Technology and 4A2 - Product Driven PV Module Manufacturing Technology. Phase 5A was also divided into 2 parts, 5A1 PV System and Component Technology and 5A2 - PV Module Manufacturing Technology. Phases 4A and 5A objectives include stimulating a broader interest in the production of PV products. In addition, these two phases are intended to encourage system and product integration, increase module production capacity, and reduce PV module production costs. Finally, 4A and 5A are expected to stimulate advances in PV systems and components, and developments in design leading to overall reduced system life-cycle costs of the PV end-product. Manufacturing flexibility with the associated cost reduction, improved efficiency, and broader market applications for PV systems as a whole are also emphasized. All work in the PVMaT project is managed by a Technical Monitoring Team consisting of engineers and scientists from NREL and Sandia National Laboratories (SNL).

Of the thirteen subcontracts awarded in Phase 4A, eight are in Phase 4A1. These eight are now just completing their work, which deals with manufacturing generally related to PV-system components such as inverters, and system integration efficiency and design improvements. Four subcontracts are being negotiated under Phase 5A1. These address system integration or manufacturing enhancements generally related to PV system components and aspects other than modules, e.g., batteries, inverters, and/or system integration efficiency and/or design improvements. Progress in Phases 4A1 and 5A1 is summarized below. Progress in Phases 4A2 and 5A2 is reported at this conference in a paper by C. Edwin Witt, et. al.

## PHASE 4A1 PRODUCT AND MANUFACTURING ADVANCEMENTS

**Table 1**

**Phase 4A1 Subcontractors**

| | |
|---|---|
| Ascension Technology, Inc. | Manufacture of an AC Photovoltaic Module |
| Advanced Energy Systems | Next Generation Three Phase Inverter |
| Evergreen Solar, Inc. | Advanced Polymer PV System |
| Omnion Power System Engineering Corp. | Three-Phase Power Conversion For Utility Interconnected PV Applications |
| Solar Design Associates, Inc. | The Development of Standardized, Low-Cost AC PV Systems |
| Solar Electric Specialties | Design, Fabrication and Certification of Advanced Modular PV Power Systems |
| Trace Engineering | Modular Bi-directional DC to AC Power Inverter Module for PV Applications |
| Utility Power Group, Inc. | Development of a Low-Cost Integrated 20-kW AC Solar-Tracking Sub-array for Grid-Connected PV Power System Applications |

Work completed by four of the Phase 4A1 companies can be grouped in the general category of manufacturing improvements for PV system integration. Progress by each follows, listed in alphabetical order.

Ascension Technology, Inc. (ATI) completed product enhancements and established the manufacturing capability for the fully-integrated 'SunSine$^{TM}$300 AC Module.' This product, rated at 250-Wac Standard Test Conditions (STC), consists of the SunSine$^{TM}$300 AC inverter attached to the back of the ASE Americas, Inc. large-area PV laminate (260- to 300-Wdc). The AC Module can be configured for output into a 120/240Vac split-phase or 120/208 Vac three-phase connection. The integrated unit is Underwriters Laboratories (UL)-listed, National Electrical Code (NEC) compliant and meets Federal Communications Commission (FCC) standards for electromagnetic interference. It is sold as a complete power unit, ready for utility interconnection, and is compatible with the Ascension RoofJack$^{TM}$ mounting system for rapid, low-cost installation. Features of the SunSine$^{TM}$300 inverter include a plug-in connector for rapid 'AC Module' assembly and quick-connectors for rapid installation with no DC field-wiring needed [5]. The SunSine$^{TM}$300 features include passive and active anti-islanding protection and maximum power point tracking. ATI recently completed a pilot production run, to ISO 9001 standards, of 109 'SunSine$^{TM}$300 AC Modules' with 100% successful operation at start-up. A production run of 200 'AC Modules' is now in progress.

Solar Design Associates, Inc. teamed with Solarex and Advanced Energy Systems, Inc. (AESI) to improve reliability and safety and reduce costs through standard pre-engineered components for standardized, low-cost PV systems [6]. AESI completed product enhancements for their MI-250 MicroInverter, including software controls, power-line carrier monitoring and anti-islanding protection. This ac inverter unit is UL- listed, FCC compliant, and can be ordered in export voltage ranges. Solarex developed a low-cost pre-engineered assembly for mounting a PV array. The standardized system combines framing and mounting the PV array and incorporates electrical interconnection, array wiring, grounding and lighting protection into the frame. With features such as quick-connect wiring and approved, simplified grounding, PV systems can be rapidly installed at minimal cost. A recent 1-kW Solarex demonstration installation using thin-film modules was completely installed and operational, including the utility interconnection, in approximately 4 hours.

Solar Electric Specialties (SES) completed manufacturing improvements as part of their effort to increase standardization and modularity in integrated, factory-packaged PV systems. The benefits to this approach are shorter lead times with lower materials costs, higher overall quality and system reliability, decreased management and engineering time, and lower installation labor. In addition, SES made a concerted effort to achieve safety and performance listings for both product lines, including UL- listing and Factory Mutual (FM) approval. Their approach for standardized product lines simplifies the process for customers to specify systems for particular needs. An important corollary to SES' standardized products and the products' compliance to standard safety measures is these factors give lending institutions greater confidence in the product, resulting in easier customer financing.

SES used two product lines, the SES Modular Autonomous PV Power Supply (MAPPS) and a mobile 1-kW Photogenset, to establish this approach. The MAPPS product line is a stand-alone PV power system consisting of PV modules, solid-state power control systems, sealed batteries and enclosures for the batteries and power control system. Products are available with outputs ranging from 12 - 48 Vdc and the entire product line is UL- listed and FM approved [7]. The Photogenset product line combines a propane-powered generator (with an remotely-controlled oil-changer) integrated with a PV array and battery storage to provide off-grid AC power. The 1-kW mobile system used to establish the processes for this SES product line includes of a fully enclosed trailer containing a 4-kW inverter, micro-processor-based power controller with full remote communications capabilities, 2-channel PV combiner box and wiring protection (disconnects and over-current protection) designed to meet UL safety standards. Although the system design and component selection were based on code requirements, this product is not UL- listed, as the company was unable to obtain a UL- listed generator.

Utility Power Group, Inc. (UPGI) completed manufacturing modifications and power processing improvements for larger utility interactive (U-I) systems. Based upon their utility-scale PV demonstration installations, UPGI determined that the most important factor to reduce costs and improve reliability was to bring as much of the field installation work as possible onto the factory floor, where labor is more efficient and assembly more consistent. UPGI's approach was to address the PV modules and power conversion and control separately, and to develop integrated, factory-assembled methods for each. For PV modules, UPGI established a manufacturing process for integrating PV laminates into pre-assembled, field-deployable modular panels which can be assembled into 7- to 15- kW sub-arrays. UPGI assembles laminates into Modular Panels (MPs) consisting of several Siemens frameless laminates, either Model M-55 or SP7 (depending upon the size of the system that is ordered), adhesively attached to 'C'-shaped steel mounting rails. Laminate interconnection is also accomplished on the factory floor. The pre-assembled MPs are then mounted into recyclable shipping fixtures and delivered to the field ready for placement on the ground support structures [8].

For power conversion, UPGI streamlined assembly by integrating power conversion/control electronics, array-tracking control electronics, source-circuit protection hardware, and DC and AC switchgear into a single, pre-assembled unit termed an Integrated Power Processing Unit (IPPU). The tracking mechanism for each sub-array is attached to the back of the 3-compartment enclosure. The IPPU's 3-phase inverter is 96% efficient with less than 3% total harmonic distortion (THD) over a 25% to 100% output range. The IPPU is shipped ready for connection at the center of each sub-array. Ancillary to factory assembly, UPGI refined the field installation methods for these systems. The company accomplished their objectives, achieving a 40% reduction in area-related balance-of-system costs and reducing net total costs of their single-axis-tracking PV systems by 23%. At the time of writing this paper, UPGI has deployed or contracted to place 10 systems totalling 2.5 MW.

Three Phase 4A1 subcontractors worked toward manufacturing enhancements and product improvements related to PV inverters. Achievements of each are described below, in alphabetical order.

Advanced Energy Systems, Inc. (AESI) improved product reliability and institute design modifications to simplify manufacturing and maintenance. They integrated subcomponents into compact, readily serviceable units [9]. The AESI design incorporates digital inverter control and all inverter controllers (3-phase) integrated onto a single printed circuit board. AESI also integrated power functions into a modular 'PowerBlock,' combining the Insulated Gate Bipolar Transistor (IGBT) power switching subassembly, heat sink, fans and capacitors, simplifying factory testing and field maintenance. Another significant step was to incorporate communication, data-logging and remote trouble-shooting capabilities into the product. AESI is demonstrating their results with a hybrid and a utility-interactive 60-kW inverter designed for fully automatic, unattended operation. The performance characteristics of the PV- wind hybrid unit include input voltages of 189 - 324Vdc, output voltages of 3-phase 480Vac, 60 Hz. Performance characteristics of the Utility-Interactive (U-I) unit include 95% peak efficiency, less than 5% THD, anti-islanding protection, and internal circuit protection in the case of excess dc input voltages.

Omnion Power Engineering Corp. (Omnion) is developing a 100-kW U-I power conversion system using a highly-integrated power switching assembly with the IGBT's laminated directly to the heat sink. The laminated power-switching assembly results in lower losses, smaller heat sinks, reduced factory labor and assembly time. Omnion estimates manufacturing costs, in lots of 100 units, will be less than US$0.25/$W_p$ [10]. The unit's design was influenced by round-table discussions with system users, integrators and utilities to define the most useful parameters for this product. Performance characteristics include a 93% peak efficiency, a 300 - 600Vdc input voltage window, with an operating voltage range of 252 - 308Vac at 59-61Hz. Omnion has emphasized reliability in this product line and will use ISO9001 qualification procedures in their design process and in manufacturing. The unit is designed for a calculated mean time before failure design goal of 40,000 hours. The product can be enhanced with optional features such as enhanced data acquisition suggested by the round table advisors. The unit is designed to comply with applicable UL, IEEE, NEC and FCC guidelines.

Trace Engineering streamlined their production manufacturing and improve reliability through a modular, basic building-block inverter design for stand-alone, hybrid or U-I applications [11]. The building block can operate in parallel, in series, single-, split- and 3-phase applications. This universal 'building block' design is intended to reduce Trace Engineering's manufacturing costs while maintaining sufficient versatility and compatibility with current inverter models. Trace Engineering used a 2-kW unit to demonstrate their approach, and elements of this design have already been incorporated into current Trace Engineering products. In addition, Trace Engineering developed modular, UL -listed packaging also expandable for a variety of applications.

Evergreen Solar, Inc.'s area of work is unique in Phase 4A1, as their work combined developments in module-related advancements. Based upon the knowledge about the variety of polymeric materials on the market, Evergreen evaluated alternative materials to improve PV panel manufacturing and PV system installation. The company identified two materials. The first is a transparent encapsulant laminated in air. This material permitted Evergreen to develop a continuous, non-vacuum lamination process for PV panels using heated rolls. The encapsulant has reported material costs lower than EVA-based materials currently in use [12]. Evergreen also identified a PV panel backskin material. This material, used to replace Tedlar$^{TM}$, can also be applied as an edge sealant which eliminates the need for a frame as it is strong enough to protect the edges of the glass superstrate. The backskin is also highly puncture resistant, with low permeability and high adhesion characteristics. The company capitalized on these multiple qualities to develop their Innovative Mounting System (IMS), where a mounting rail adheres to the back of the module for rapid, easy panel installation in the field. These advancements are discussed in depth in papers by J. I. Hanoka at this conference.

## PHASE 5A1 PRODUCT AND MANUFACTURING ADVANCEMENTS

Four Phase 5A1 subcontractors (Table 2) are now working on product enhancements, streamlined manufacturing and cost reduction (exclusive of PV modules) with an emphasis on residential PV applications. Their plans are summarized below.

**Table 2**
**Phase 5A1 Subcontractors**

| | |
|---|---|
| Ascension Technology, Inc. | Cost Reduction and Manufacture of the SunSineTM325 AC Module |
| Omnion Power Engineering Corp. | Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV |
| PowerLight Corp. | PowerGuard$^{R}$ Advanced Manufacturing |
| Utility Power PV Group, Inc. | Development of a Fully-Integrated System for Residential Applications |

ATI is refining the SunSine$^{TM}$300 inverter for improved manufacturabilty, lower cost and enhanced performance. Their goals are to achieve a 40 - 50% cost reduction in the SunSine$^{TM}$ inverter, reduce the overall footprint of the unit, increase peak efficiency, achieve 270-Wac (STC) rating and establish a 5,000 units per year production capability with less than 0.1% failure at startup. ATI plans to achieve the performance and manufacturability improvements by incorporating a soft-switching topology. With this modification the inverter is expected to achieve higher efficiency through reduced switching losses, when compared to the hard-switched approach in the current design. The enhanced product will be called the 'SunSine$^{TM}$325 AC Module,' and ATI plans to obtain UL- listing, FCC Class B verification and other markings as needed for export products. The SunSine$^{TM}$325 will use the ISO9001 quality assurance during manufacture and the new design will undergo highly accelerated life tests (HALT) procedures to ensure long-term reliability.

Omnion plans to complete design enhancements to produce Series 2500 1- and 2-kW inverters that are easily manufactured and suitable for use in residential applications. These inverters will be for U-I applications and meet design requirements for high-volume production (5,000 units/year). This product will use the transformerless, phase-leg topology of the Omnion Series 2200, but with enhancements for a larger input voltage range of 180 to 500Vdc, making it easier to design systems using the broader array voltage windows presented by some thin-film PV arrays. Omnion expects this approach to result in lighter, more efficient, lower cost 1-kilowatt and 2-kilowatt inverters. This product line will also use the ISO9001 quality assurance during manufacture and the new design will undergo highly accelerated life tests (HALT) procedures to ensure long-term reliability.

A third company in this group, PowerLight Corporation (PowerLight) plans a three-year program to accomplish enhancements to their PowerGuard$^{TM}$ product, a light-weight, electrically-active roof tile, which can be mounted without roof penetrations in most applications. PowerLight plans advancements in manufacturing to reduce cost, increase capabilities and provide PV systems incorporating financing options. PowerLight expects to demonstrate system costs of $3.05/W and complete PowerGuard$^{R}$ tile fabrication manufacturing improvements to achieve production capacity of 16 MW/yr. The products will be produced to meet UL and international requirements and integrated warranties will be developed. Each year commercial demonstrations of the modified PowerGuard$^{R}$ systems will be evaluated. In addition, PowerLight is working with Trace Technologies to upgrade the control board for their grid-tied inverter. Advancements include redesigning the controller for PV-specific applications, adding an integrated data acquisition system, and establishing communications for audit-worthy verification of PV system performance. The improvements will apply to a complete line of Trace Technologies' advanced inverter products from 25- to 300-kW.

UPGI plans to reduce the total installed cost and increase the reliability of residential roof-top mounted PV systems and meet market requirements for a U-I PV system with storage. Through a range of integrating steps, UPGI plans to achieve a 30% reduction in total non-module-related system costs. The fully integrated system will incorporate roof-top PV modules, a 4- to 6- kW power unit and an optional battery storage unit. The power conditioning components will be designed to support a variety of laminates, including the Seimens and Evergreen crystalline silicon, and Solarex a-silicon products. The system will conform to applicable standards, building and seismic codes, and be adaptable to a wide range of roof materials for both new and retrofit applications. The results will be demonstrated through a pilot production run and beta testing a variety of locations.

## SUMMARY

The system and component manufacturing advancements accomplished to date have resulted in improved reliability and greater variety of integrated U.S. PV products. Manufacturers report they are now producing more versatile products that are easier and less expensive to build, with demonstrated reliability, simplified commissioning and ready serviceability. Advanced systems range in size from 260-Wac to 15-kWac and advanced inverter products range from 250-Wac to 100-kWac. Products and systems resulting from this project are now in use.


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