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

1. 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, is divided into two parts: 4A1 - Product-Driven System and Component Technology and 4A2 - Product Driven PV Module Manufacturing Technology. Phase 5A is also divided into two 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, Phases 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 the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (SNL).

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.

2. PHASE 4A1 PRODUCT AND MANUFACTURING ADVANCEMENTS

Of the thirteen subcontracts awarded in Phase 4A, eight are in Phase 4A1. These eight are now completing their work, which deals with manufacturing generally related to PV system components, such as inverters, and system integration efficiency and design improvements. The companies and their related research and development topics are listed in Table I.

2.1 Phase 4A1 Developments in PV Systems and System Integration

Work completed by five of the Phase 4A1 companies can be grouped in the general category of manufacturing improvements for PV system integration. Descriptions of their progress follows, presented in alphabetical order.

Ascension Technology, Inc. (ATI) completed product enhancements and established the manufacturing capability for the fully integrated "SunSine™300 AC Module." This product, rated at 250 Wac at Standard Test Conditions (STC), consists of the SunSine™300 AC inverter attached to the back of the ASE Americas, Inc., large-area PV

laminate (260 to 300 Wdc) (Fig. 1). The AC Module can be configured for output into a 120/240 Vac split-phase or 120/208 Vac three-phase connection. The integrated unit is 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™ mounting system for rapid, low-cost installation. Features of the SunSine™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™300 AC inverter 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™300 AC Modules with 100% successful operation at start-up. Over 100 units have been installed and a production run of 200 AC Modules is now in progress.

Table 1: Subcontractors now completing work in PVMaT Phase 4A1 and topics of their work.

Company	Title
Ascension Technology, Inc.	Manufacture of an AC Photovoltaic Module
Advanced Energy Systems, Inc.	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

Evergreen Solar, Inc. combined several developments in module-related advancements. Based on their knowledge about the variety of polymeric materials on the market, Evergreen evaluated alternative materials to improve PV-panel manufacturing and PV-system installation. After testing and evaluation, the company identified two materials. The first is a transparent encapsulant laminated in air. This material permitted Evergreen to develop a continuous, non-vacuum

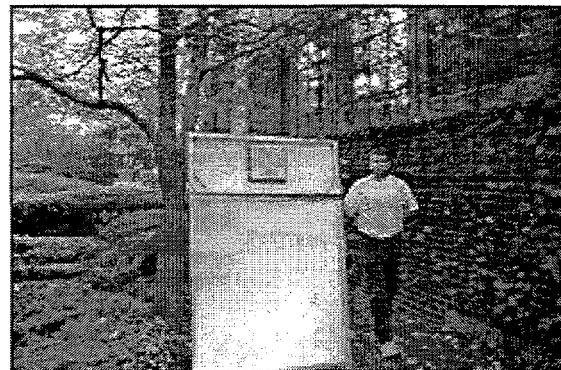


Figure 1: Back of Ascension Technology's "SunSine300™ AC Module" illustrating the AC inverter.

lamination process for PV panels using a heated-roll method. The encapsulant has reported material costs lower than EVA-based materials currently in use [12]. Evergreen also identified a PV-laminate backskin material. This material, used to replace Tedlar™, can also be applied as an edge sealant. This backskin material 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 vapor permeability and high adhesion characteristics. The company capitalized on these multiple qualities to develop their Innovative Mounting System, where a mounting rail adheres to the back of the module for rapid, easy, panel installation in the field. Both these advancements are discussed in depth in papers by J. I. Hanoka at this conference.

Solar Design Associates, Inc. teamed with Solarex and Advanced Energy Systems, Inc. (AESI) to improve reliability and safety and to reduce costs through pre-engineered components for standardized, low-cost PV systems [6]. AESI completed product enhancements for their MI-250 MicroInverter, including software controls and power-line carrier monitoring. This AC inverter 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 lightning protection into the frame. With features such as quick-connect wiring and approved, simplified grounding, PV systems can be rapidly installed at minimal cost. For example, a recent 1-kW Solarex system demonstration using thin-film modules was completely installed and operational, including the utility interconnection, in less than 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 two product lines, discussed below, 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 products, a 200 Wdc 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. UL-listed and FM-approved products are available with outputs ranging from 12 - 24 Vdc[7]. The Photogenset product line combines a propane-powered generator (with an automatic oil-changer) integrated with a PV array and battery storage to provide off-grid AC power (Fig. 2). The 1-kW mobile system used to establish the processes for this SES product line includes a fully enclosed trailer containing a 4-kW inverter, a micro-processor-based power controller with full remote communications capabilities, a 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.

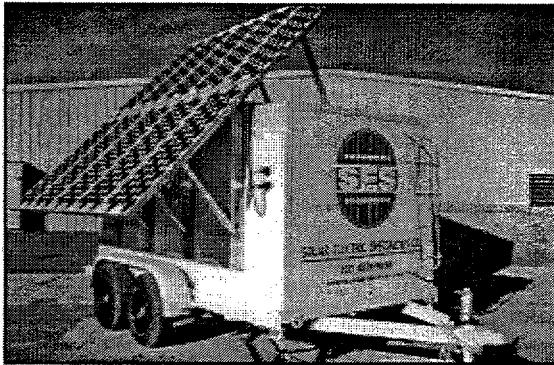


Figure 2: Solar Electric Specialties 1 kW Photogenset, shown in the trailer-mounted configuration.

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 factory assembly 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].

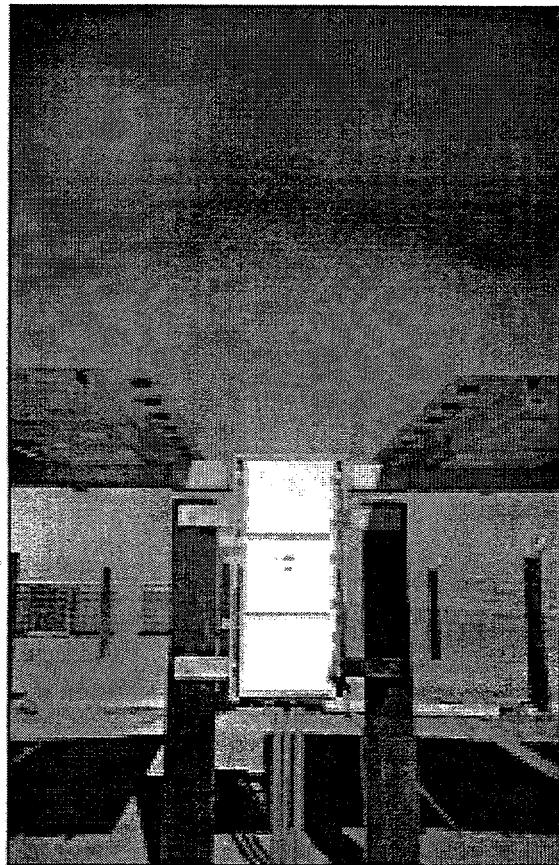


Figure 3: Photo by Utility Power Group, Inc. illustrating the Integrated Power Processing Unit and factory-assembled Modular Panels.

For their 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) (Fig. 3). UPGI attaches the tracking mechanism for each sub-array to the back of the IPPU's enclosure prior to shipment to the site, so the unit arrives ready for connection at the center of each sub-array. The IPPU's 3-phase inverter is 96% efficient with less than 3% total harmonic distortion (THD) over a 25% to 100% output range. UPGI also 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.

2.2 Phase 4A1 Inverters

Three Phase 4A1 subcontractors are completing manufacturing and product improvements related to PV inverters, described below in alphabetical order.

Advanced Energy Systems, Inc. (AESI) improved product reliability and instituted design modifications to simplify manufacturing and maintenance, and consolidated subcomponents into compact, readily serviceable units [9]. For example, the digital inverter control and all inverter controllers (3-phase) are incorporated into 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. 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 - 324 Vdc, output voltages of 3-phase 480 Vac, 60 Hz. Performance characteristics of the Utility-Interactive (U-I) unit include 95% peak efficiency, less than 5% THD, and internal circuit protection in the case of excess DC input voltages.

Omnion Power Engineering Corp. is developing a 100-kW U-I power-conversion system using a highly integrated power-switching assembly with the IGBTs laminated directly to the heat sink. The laminated power-switching assembly results in lower losses, smaller heat sinks, and reduced factory labor and assembly time. 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 inverter efficiency, a 300 - 600 Vdc input voltage window, with an operating voltage range of 252 - 308 Vac at 59-61 Hz [10]. 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 upgraded 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 product manufacturing and improved reliability through a modular, versatile building-block inverter design for stand-alone, hybrid, or U-I applications [11]. The building block can operate in parallel or in series for 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 2.5-kW unit to demonstrate their approach, and elements of this design have already been incorporated into current Trace Engineering products. In addition, Trace developed a modular, UL-listed inverter and BOS packaging system, readily expandable for a variety of applications.

3. PHASE 5A1 PRODUCT AND MANUFACTURING ADVANCEMENTS

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, and emphasize residential applications. The companies and their planned work are summarized in Table 2 and described below.

Table 2: Planned subcontractors and their research and development topics for Phase 5A1.

Company	Title
Ascension Technology, Inc.	Cost Reduction and Manufacture of the SunSine™325 AC Module
Omnion Power Engineering Corp.	Manufacturing and System Integration Improvements for One- and Two-Kilowatt Residential PV Inverters
PowerLight Corp.	PowerGuard® Advanced Manufacturing
Utility Power Group, Inc.	Development of a Fully-Integrated PV System for Residential Applications

ATI is refining the SunSine™300 inverter for improved manufacturability, lower cost, and enhanced performance. Their goals are to achieve a 40-50% cost reduction in the inverter, reduce the overall footprint of the unit, increase peak efficiency, achieve a minimum 270 Vac (STC) rating and establish a production capability of 5,000 units per year, with less than 0.1% failure at start-up. ATI plans to achieve improvements in the AC inverter performance and manufacturability 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™325 AC Module," and ATI plans to obtain UL-listing, FCC Class B verification, and other markings as needed for export products. Manufacture of the SunSine™325 AC Module will apply ISO9001 quality assurance procedures, and the new inverter design will undergo highly accelerated life tests (HALT) procedures to ensure long-term reliability.

The work with *Omnion* is now under negotiation. The company 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 500 Vdc, 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- and 2-kW inverters. This product line will also use the ISO9001 quality assurance during manufacture and the new design will undergo HALT procedures to ensure long-term reliability.

A third company in this group, *PowerLight Corporation*, plans a 3-year program to accomplish enhancements to their PowerGuard^R product, a light weight, electrically active roof tile that can be mounted without roof penetrations in most applications. PowerLight plans advances 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 to complete improvements in PowerGuard^R tile fabrication manufacturing to achieve a production capacity of 16 MW/yr. The products will be produced to meet UL and international requirements, and integrated warranties will be developed. Commercial demonstrations of the modified PowerGuard^R systems will be evaluated each year. In addition, PowerLight is working with Trace Technologies (a sister company to Trace Engineering) 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. Power-conditioning components will be designed to support a variety of laminates, including the Siemens and Evergreen crystalline silicon, and Solarex amorphous-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 at a variety of locations.

4. 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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