NREL/SR-520-23118 • UC Category: 1280 • DE97006928

Development of a Low-Cost Integrated 20-kW ac Solar Tracking Sub-Array for Grid-Connected PV Power System Applications

Phase I Annual Technical Report 11 July 1995 - 31 July 1996

M. Stern, R. West, G. Fourer,
W. Whalen, M. Van Loo, and G. Duran
Utility Power Group
Chatsworth, California

NREL technical monitor: H. Thomas

National Renewable Energy Laboratory
1617 Cole Boulevard
Golden, Colorado 80401-3393
A national laboratory of
the U.S. Department of Energy
Managed by Midwest Research Institute
for the U.S. Department of Energy
under Contract No. DE-AC36-83CH10093

Prepared under Subcontract No. ZAF-5-14271-06

June 1997

Available to DOE and DOE contractors from:
Office of Scientific and Technical Information (OSTI)
P.O. Box 62
Oak Ridge, TN 37831
Prices available by calling (423) 576-8401

Available to the public from:
National Technical Information Service (NTIS)
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
(703) 487-4650

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

TABLE OF CONTENTS

Page

LIST OF FIGURES

DEFINITIONS

Throughout this report, the following definitions shall apply to the words listed below:

PV module:	An assembly of discrete PV solar cells which is manufactured by Siemens Solar Industries and utilized by Utility Power Group in the manufacture of Modular Panels.
Laminate:	A glass/EVA/cells/EVA/Tedlar encapsulated assembly with tinned copper terminal ribbons penetrating the Tedlar back sheet.
J-box:	A weather tight enclosure attached to the back of a laminate to provide a junction point between a laminate's terminal ribbons and the PV system's interconnection wiring.
Frame:	A structural element attached to the perimeter of a laminate to provide edge protection and facilitate handling and mounting.

EXECUTIVE SUMMARY

In Year One of this two year PVMaT Phase 4A1 work effort, UPG successfully completed the design, fabrication, testing and demonstration of a modular and integrated 20 kW ac solar tracking PV power system sub-array. The two key components developed are a Modular Panel which optimizes factory assembly of PV modules into a large area field deployable structurally integrated PV panel, and an Integrated Power Processing System which combines all dc and ac power collection, conversion and control functions within a single field deployable structurally integrated electrical enclosure.

UPG exceeded its goal of providing a 40% reduction in area related balance-of-system costs and a 50% reduction in power related balance-of-system costs by achieving cost reductions of 43% and 51% respectively. The net reduction in the total cost of single-axis solar tracking grid connected PV power systems achieved by UPG was 21.3%. This result changes the previous typical allocation of total system cost from 60% PV modules and 40% balance-of-system to a new allocation of 72% PV modules and 28% balance-of-system. Notwithstanding required improvements in reliability and performance, this result indicates that balance-of-system costs are no longer an obstacle to the widespread commercialization of PV technology in grid connected applications.

INTRODUCTION

The overall goal of this PVMaT Phase 4A1 work effort by Utility Power Group ("UPG") is to reduce the installed cost of utility scale grid connected photovoltaic ("PV") power systems. PV power systems generate electricity via the direct conversion of sunlight into electrical energy and can serve as an environmentally benign and domestically secure source of electricity for utility grid connected peak or intermediate load applications. Considering that almost 700,000 MW of electricity generating capacity exists in the United States alone, PV power systems have only negligibly penetrated the electricity generation market. The dominant factor limiting the use of PV power systems in grid connected applications today is the capital cost of the total installed system with respect to the annual kilowatt hours of energy generated.

The two primary PV power system capital cost groups are 1) PV Modules and 2) Everything Else, which is more commonly referred to by the acronym "BOS" (Balance-Of-System). In general, 60% of the capital cost of typical grid connected PV systems is allocated to the PV modules while 40% of the costs are allocated to BOS. Both cost groups are highly affected by production and installation volume which permits standardization, automation, and integration.

The focus of UPG's work effort is on BOS component manufacturing technology, which essentially involves all PV power system engineering, manufacturing, assembly and construction tasks from the receipt of a PV module to the delivery of grid connected electricity. Working with Siemens Solar Industries (Camarillo, California) to optimize the design of PV modules for power systems applications, UPG's goal is to obtain and demonstrate significant cost reductions in the installed cost of PV power systems.

As a leading provider of PV system engineering and construction services, UPG is able to quickly transfer any such cost reductions into the PV power system marketplace. UPG has received orders to manufacture and install over 40 integrated single-axis solar tracking Sub-Arrays from electric utility customers during Phase II of this PVMaT contract. Single axis solar tracking provides over 20% more energy in a typical year than a fixed axis PV system.

BACKGROUND

Utility Power Group was formed in 1985 by a team of dedicated and experienced engineers and scientists to commercialize photovoltaic (PV) electricity generation technologies in grid and non-grid connected electric utility applications. From 1985 to 1992, UPG's primary focus was on developing advanced thin film PV module manufacturing technology, and from 1992 onward, the company's focus shifted to providing PV power system design, engineering, construction, installation, operation and maintenance services to electric utilities as well as Government and commercial facilities. In 1993, UPG provided the Sacramento Municipal Utility District with a "turn-key" 200 kW PV power system in Sacramento, California.

In 1994, UPG installed a 100 kilowatt ac PV system in Fort Davis, Texas for Central and South West Services which required a total of fifty one separate electrical enclosures to provide dc combining, conduit/wire routing, tracker control, disconnect, and inverter functions. Over 2200 PV modules were individually field installed on the array structures. A single inverter provided dc to ac power conversion, and a single tracker motor controller provided solar tracking commands.

Upon completion of this project, UPG personnel analyzed the costs associated with the construction of grid connected PV power systems to determine the potential for, and identify the barriers to, future cost savings. To summarize these analyses, it was determined that a shift in philosophy from "constructing" PV power systems to "manufacturing" PV power systems would have the greatest impact upon BOS cost reduction.

The construction approach to providing PV power systems has historically required obtaining a site specific design package, procurement of various equipment, components and materials from a wide range of vendors, and field installation of these equipment, components and materials in as efficient a manner as possible. The problem with this approach is that there is no opportunity nor incentive for the contractor to combine or integrate equipment, components and materials in the design phase. Additionally, the contractor typically performs all activity in the field where labor efficiency is effected by weather, site conditions, and travel.

A manufactured approach to providing PV power systems would require the development of standard design packages with integral involvement of the vendors of equipment, components and materials. Through intelligent mechanical and electrical integration of PV modules, array structure, and power conversion electronics, the number of discrete systems parts could be reduced and several field installation tasks could be shifted to a more efficient factory environment.

UPG's desire to shift from a construction approach to a manufactured approach dovetailed with a recent trend in the PV industry in which the PV module manufacturers are not directly involved in the sale of the PV power system. Viewing the module as a component of the complete system rather than as the controlling basis of the system will allow the contractor or supplier of the system to take advantage of a number of efficiencies related to design integration.

Having identified the development of a modular PV panel and an integrated power processing system as the most important elements in a PV power system cost reduction program, UPG received cost shared funding under Phase 4A1 of the Photovoltaic Manufacturing Technology project in July, 1995. The two year sub-contract from the National Renewable Energy Laboratory, when completed in July, 1997 will enable UPG to "manufacture" grid connected PV power systems thereby significantly reducing the capital costs of such systems and accelerating the commercialization of this important technology.

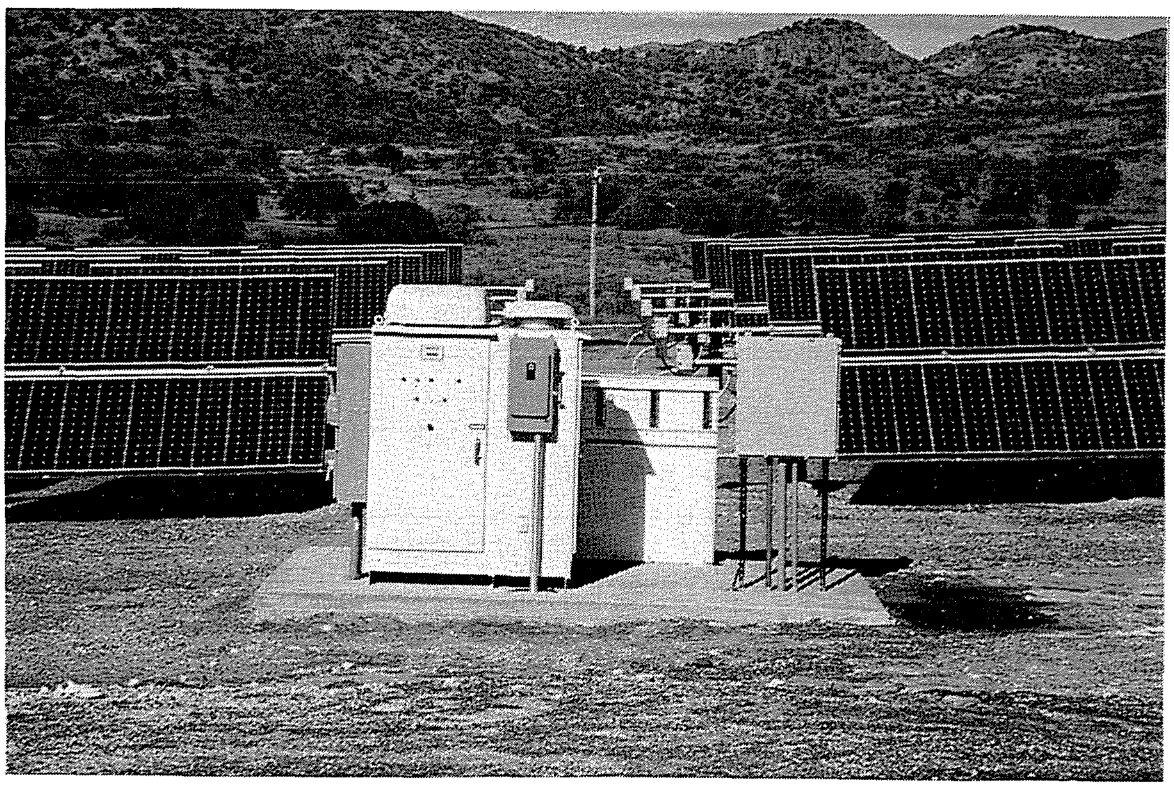

Figure 1. Photograph of 100 kW PV power system in Fort Davis, Texas.

Although the PV system in Fort Davis, Texas was based upon UPG's lowest cost single axis solar tracking array design at that time, it was not optimized for BOS cost reduction. Figure 2 provides an approximate percentage breakdown of the cost elements within the BOS cost group.

COST ELEMENT	PERCENTAGE	
Design	8	
Power Related	24	
Inverter/DAS		20
Transformer		3
Disconnects		1
Area Related	68	
Structure		26
Labor & Project Management		15
Tracker Drive		10
Foundation		5
Site Expenses		5
Electrical Enclosures		5
Wire & Conduit		2
TOTAL	100	

Figure 2. BOS cost group breakdown.

UPG's PVMaT Phase 4A1 work effort directly targets the BOS cost group and affects each of the listed cost elements. Modularity and integration of array components will significantly reduce the number of discrete field construction and installation operations required, simplify the design and construction documentation, and permit standardization of equipment, components, and materials.

OBJECTIVE

The overall objective of UPG's two year, two Phase PVMaT Phase 4A1 effort is to achieve greater than a 20% reduction in the installed cost of PV power systems. With UPG's focus on the BOS cost group, which had typically represented 40% of the total cost of a PV power system, the overall objective could be re-stated as seeking to achieve a 50% reduction in BOS costs.

TECHNICAL APPROACH

UPG's technical approach towards achievement of the above objective is based upon the following lessons learned during the construction or installation of multiple PV power systems:

- Factory assembly of BOS components provides cost savings over field assembly.
- Reducing the number of discrete BOS components reduces installation cost.
- Standardization of design reduces the cost of BOS components and materials.
- Reduction of discrete tasks reduces the cost of construction labor.

These lessons, and a desire to shift from a "construction" approach to a "manufactured" approach, led UPG to select modularity and integration as the two primary design criteria to be utilized. A modular alternating current ("ac") sub-array design would simplify the generation of specific and custom PV system design packages and reduce incremental administrative and project management costs. Redundancy and reliability are PV system operational cost factors which benefit from modularity and the reduced number of components associated with increased functional integration.

Based upon the above lessons learned and design criteria, UPG began development of an integrated and modular ac sub-array which became the foundation for the PVMaT Phase 4A1 work effort described in this report.

Specifically, UPG is developing:

- A Modular Panel (MP) which will be factory assembled and tested by Utility Power Group utilizing production optimized and reliability tested PV laminates manufactured by Siemens Solar Industries.

- A Integrated Power Processing Unit (IPPU) combining all sub-array electrical functions including power collection, system protection, direct current ("dc") to ac conversion, solar tracking, and switching into a single field deployable unit which will be factory assembled and tested by Utility Power Group.

The structural and foundation BOS cost elements are not a part of this development effort due to the marginal opportunity for cost reduction as compared to the other cost elements. Although UPG has pioneered the use of wood poles in a center supported single axis solar tracking array configuration, many other foundations and structures can provide cost effective module and panel support when properly designed. These other approaches will be investigated by UPG upon completion of the development effort described in this report.

MODULAR PANEL DEVELOPMENT

The factory assembled PV panel under development by UPG and Siemens Solar Industries (SSI) provides cost reduction to both the PV module cost group and the structure cost element. These cost reductions are achieved through:

1. Elimination of the redundant structural frames mounted to the perimeter of each module.
2. Utilization of bulk packaging for PV modules and elimination of retail consumer oriented packing materials.
3. Standardization of manufacturing based upon a large area module.
4. Simplification of the panel support structure.

UPG and SSI reviewed a number of SSI's commercially manufactured and prototype module designs to determine the optimum configuration for the Modular Panel ("MP") with the intention of developing a new PV module specifically designed for assembly into large area panels for high voltage power system applications. These designs were submitted to NREL as deliverables for this subcontract.

Figure 3 lists the primary design criteria utilized by UPG and SSI to select the module design for the MP.

ELECTRICAL	MECHANICAL	MODULE MANUFACTURING	PANEL ASSEMBLY
Voltage	Length	Cell Size	Module Size
Current	Width	String Length/Yield	Sub-Array Interface
Diodes	Terminal Location	Terminal Location	Terminal Location
UL	UL	UL	UL
NEC		Circuit Size/Yield	NEC
Wire Size		Module Size/Yield	
Area Efficiency			

Figure 3. Modular Panel design criteria.

SSI's model M55, M72, M110, and ProCharger 4 PV modules formed the baseline for this investigation, and were compared and contrasted to a number of prototype module design concepts. The key results of this analysis were as follows:

- Increasing laminate size much beyond that of the 20.5 inch (521 mm) x 47.0 inch (1194 mm) Pro4 does not offer additional incremental cost benefit due to increased yield losses and manufacturing capital equipment costs.

- Low voltage modules (paralleled strings) connected in parallel at the MP level via a bus bar approach do not offer cost benefit due to the cost of the higher current MP J-box and wiring components which would be required.

- Optimization of a low-cost singular J-box designed for module attachment at SSI and produced in high volumes will provide the best opportunity for cost reduction.

- Utilization of a UL listed PV module significantly reduces the cost and time required to obtain UL approval of the Modular Panel.

- Lower costs will be obtained by utilizing high volume commercially manufactured PV modules rather than a lower volume module designed specifically for use in the MP.

These results led UPG and SSI to the conclusion that the unframed version of the M55 module was the optimum choice for use in the prototype MP and the next generation MP would utilize an optimized J-box developed by SSI for use with the unframed Pro4 module. This new module configuration will be available during Year Two.

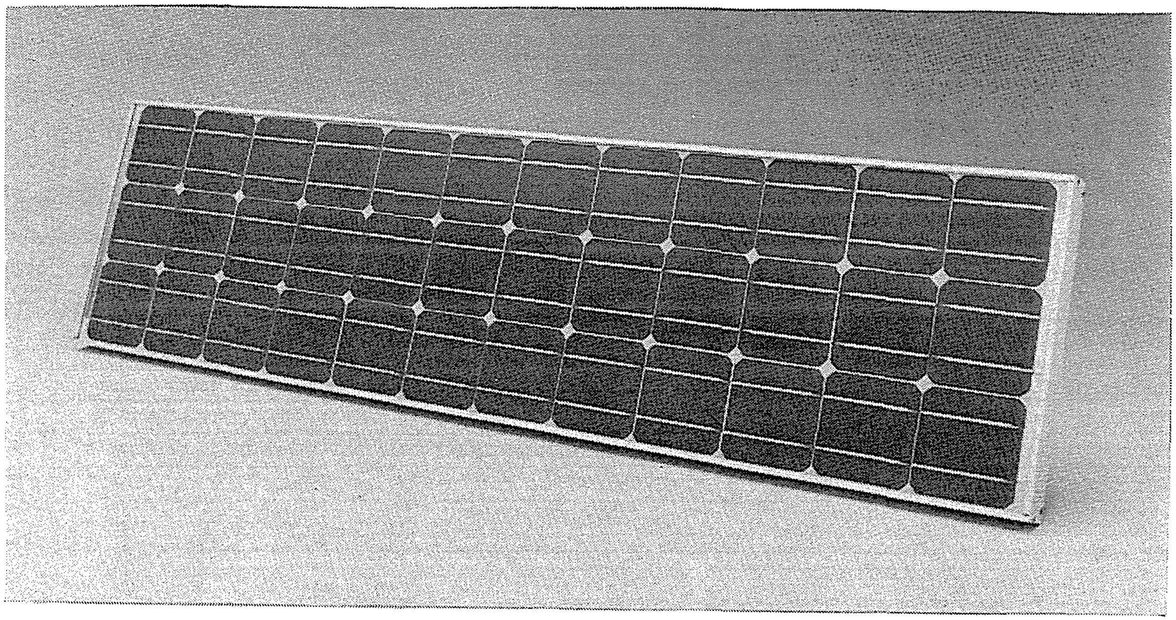

Figure 4. SSI M55 PV Module.

Based upon the selection of un-framed M-55 and Pro4 modules as the lowest cost option for the MP, the task of designing and specifying bus bar and interconnect devices was greatly simplified. Although several novel approaches were considered, the least cost option was to use a single conductor UL approved seven stranded copper USE-2 cross linked polyethylene interconnect wire between module J-boxes designed for in-series wire insertion.

An indirect module cost element which was investigated by UPG and SSI is related to the packaging of modules for shipment. Given SSI's worldwide distribution, a rugged four-pack module shipping box is utilized for all shipments of the M55 module, but requires the disposal of almost two pounds of packaging materials per module. A 100 kW PV power system may use as many as 2400 PV modules which would result in the need to dispose of over two tons of packaging material. Implementation of a bulk pack container for unframed modules within the present SSI manufacturing and material handling environment was not cost effective, but SSI developed a redesigned eight-pack shipping box which used the same amount of packaging materials as the four-pack box. This resulted in an immediate 50% reduction in the cost of shipping material, and in addition, UPG and SSI have instituted a recycling/reuse program for the packaging materials wherever possible.

Prior to the development of the Modular Panel, UPG shipped modules directly to PV power system project sites and assembled the array panels in the field. Although factory assembly of MPs offers many advantages, it nonetheless requires a second freight operation to transport the completed MPs to the project site. Additionally, the packing efficiency of MPs is not as high as modules and therefore more truckloads are required to transport MPs than modules.

Development of a suitable container or enclosure to transport the MPs proved to be more challenging than originally anticipated given the physical size and weight of the MP, and the sensitivity of unframed module edges to damage from impact. After consideration of several designs and their fabrication costs it became apparent that the container concept for MP shipment was not acceptable. UPG investigated several new concepts and focused on one which utilizes the MPs themselves as structural elements of a shipping "block". To eliminate glass-to-glass contact, a reusable steel fixture was designed to link a number of panels together in a transportable block. Building this block upon the wooden pallet on which the modules were shipped facilitates movement by forklift and pallet jack as well as serving to reuse the pallet.

Electrical and structural issues served to determine the physical design size of the Modular Panel. Due to shipping, handling, and wind load considerations, UPG determined that the length of the panel should not exceed thirteen feet. To optimize materials and sub-array area utilization, the panel should not be less than nine feet in length. Electrically, the series voltage derating requirements of UL Standard 1703 and the 1996 NEC limits the open circuit voltage of a series sub-circuit to the equivalent of twenty-two (22) M-55 modules or fourteen (14) Pro4 modules. These issues combined to indicate that a MP should contain either eleven (11) M-55 modules or seven (7) Pro4 modules connected in series. A sub-circuit would then be created by connecting two M-55 panels or three Pro4 panels in series. UPG established 11M55 as the model number for the prototype Modular Panel based upon the Siemens Solar Industries Model M-55 PV module.

Structural components fabricated from both aluminum alloys and steel were evaluated for use within the MP with consideration given to weatherability, strength, cost, and galvanic compatibility. Superior in all areas of importance, steel was selected as the material of choice for the primary structural component to combine modules into a unitized panel.

The simplest and lowest cost panel structural configuration centers the modules side by side over two parallel steel section lengths, or rails. UPG selected a thin section "C" structural shape for the rail based upon its high strength to weight ratio and the ease with which holes can be located along its length. Galvanized sheet steel was selected for its corrosion resistance and galvanic compatibility with the primary sub-array structure. The rail therefore is quite similar to a standard structural "stud" widely used throughout the construction industry. The use of high volume commercially available materials significantly reduces the cost of the MP's structural components and reflects UPG's overall design philosophy to use commercially available standard components wherever possible.

Elimination of module frames dictates that the only means available for module attachment to the panel rails are clips, adhesives, or a combination of both. It became apparent that there were advantages and disadvantages associated with each of these approaches and that there was not a significant cost differential between them. Having utilized adhesives in a previous array constructed at PVUSA, UPG selected a two component adhesive system in which one component provides initial adhesion to facilitate factory assembly of panels, and the second component provides long term high strength adhesion to withstand wind loading under a wide range of environmental conditions.

Siemens Solar Industries produced several hundred M55-LJ sample modules (PV laminates) as well as the eight pack boxes to ship them to UPG. Over twenty five (25) prototype 11M55 Modular Panels were fabricated and tested utilizing these sample modules. Following is an assembly-level drawing of the Modular Panel (MP) utilized in the fabrication of the panels.

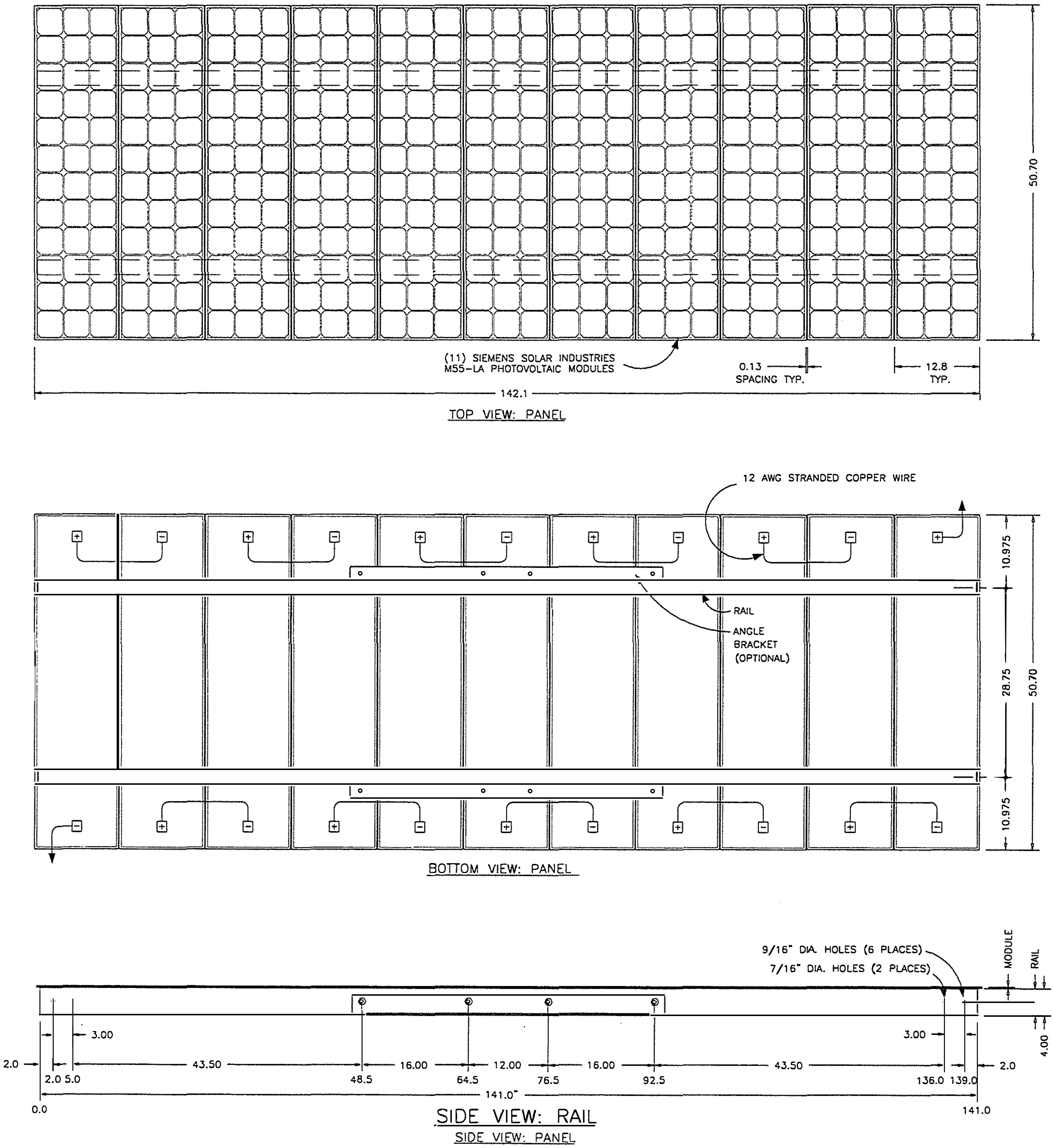

Figure 5. 11M55 Modular Panel.

Eight MP shipping fixtures were fabricated and tested by assembling eight prototype panels into a block as illustrated in Figure 6 and shipping the block via a common carrier for a distance of 700 miles between Chatsworth, California and Sacramento, California. The block was unloaded and reloaded at each destination and the trip repeated four times. The MPs arrived without damage and additional fixtures were fabricated for use on subsequent UPG PV power system projects requiring the Modular Panel.

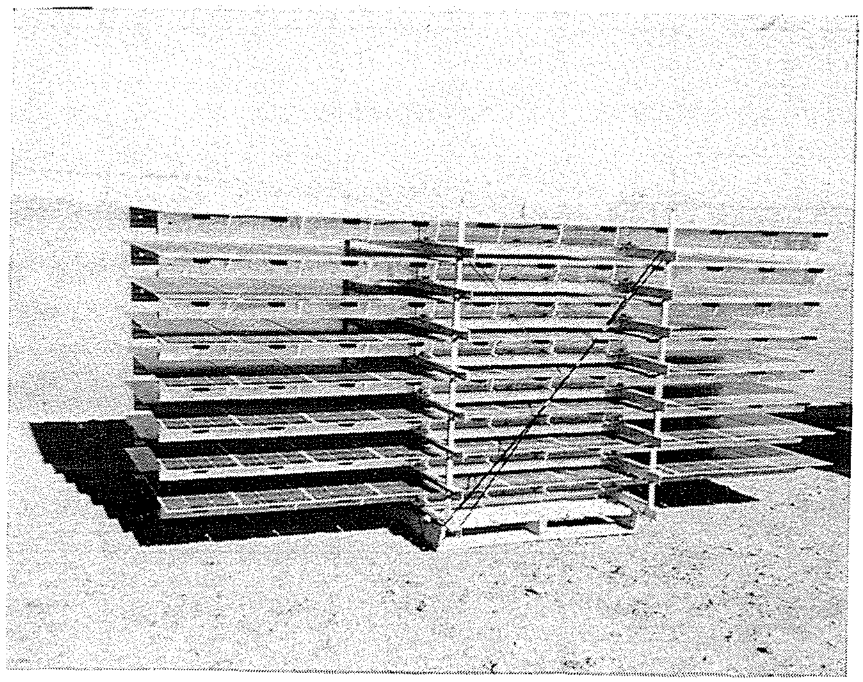

Figure 6. MP shipping block.

Testing was performed on both the M-55 module and 11M55 Panel by UPG and SSI to obtain listing approval from Underwriters Laboratories under the requirements of Standard 1703. All samples submitted for testing met or exceeded all required levels of performance including those under IEEE Standard 1262-1995 for ground continuity, dry hi-pot, and wet resistance.

UPG received Underwriter's Laboratories listing for the Model 11M55 Panel in April 1996, and with a STC rating of over 600 watts, the 11M55 is believed to be world's highest power UL listed PV panel.

IPPU DEVELOPMENT

The integrated power processing unit ("IPPU") under development by UPG provides cost reductions to both the area related and power related cost elements of the BOS cost group. These cost reductions are primarily achieved through the consolidation and optimization of the following functions:

- Series sub-circuit protection
- DC bus disconnect
- Solar tracking control
- Tracker drive motor control
- Inverter
- AC disconnect

The primary IPPU design criteria were as follows:

- Use of standard components
- Low power loss/high efficiency
- Compact geometry
- UL spacing requirements
- Ease of assembly
- Ease of troubleshooting
- Low cost

Printed circuit board (PCB) technology was selected by UPG to serve as the foundation for the IPPU sub-assemblies to simplify fabrication, testing, assembly, and field maintenance. Each sub-assembly performs a number of IPPU functions as detailed in Figure 7.

DC INTERFACE PCB ASSEMBLY

- PV sub-circuit conductor termination
- PV sub-circuit conductor overcurrent protection
- Visible dc disconnect
- Blocking (paralleling) diodes
- Lightning transient protection
- Crowbar function
- DC contactor
- DC current sense, regulation and DAS
- DC ground fault current sense
- DC bus precharge and discharge

AC INTERFACE PCB ASSEMBLY

- 3-phase utility conductor interface
- Fused power distribution
- AC contactor (bridge isolation)
- Regulated control power supply
- Tracker drive motor relays and interface
- Utility voltage sense
- Output inductor interface
- Output EMI filter
- DAS interface point

BRIDGE / REGULATOR PCB ASSEMBLY

- 20kHz 3-phase ultra fast IGBT bridge
- Opto isolated IGBT drivers
- Digitally synthesized sinewave referenc
- Phase locked loop line sync circuit
- Output sinewave current regulation
- DC voltage sense
- Bus voltage regulation
- Fast line-overcurrent detection

CONTROL PCB ASSEMBLY

- Start, wake-up, disable and stop logic
- Machine state logic

- Diagnostics and fault detection
  - Lowpower (nightly shutdown)
  - Overpower, overvoltage bus
  - Line synchronization error
  - Frequency out of tolerance
  - Utility voltage imbalance, blown fuse
  - Utility undervoltage
  - Utility overvoltage
  - System fault, output current imbalance
  - Control logic fault, undervoltage
  - Overtemperature
  - DC ground fault
  - Smoke detected
  - Tracker drive fault
  - Disable, local or remote
- Electrical max power point tracking
- DC power calculator
- LCD display driver
- Tracker drive logic and user interface

DAS BOARD OPTION

- Machine state information
- Fault delineation
- 3-phase ac power calculator
- Analog a/d conversion
- Phase a current
  - Phase b current
  - Phase c current
  - AC line voltage
  - AC kilowatts
  - DC voltage
  - DC amps
  - DC kilowatts
- Remote enable / disable interface
- Isolated RS485 link to modem

Figure 7: IPPU Sub-Assembly Functions.

Specifications were derived for each functional group based upon the following general IPPU specifications and were analyzed to ensure performance and interface compatibility. UPG's goal was to not only integrate all sub-array functions into a single unit, but also to develop an inverter with a higher switching frequency, a higher conversion efficiency, and a lower cost than is commercially available.

General IPPU Specifications

Utility Interface, 3-phase	100/173*
Nominal Power Rating	14.5 kW
Maximum Output Power	17 kW
Power Factor, 25%-100% Output	>.99
Frequency, Nominal	60 Hz
Current Distortion, 25%-100% Output	<3% THD
3-Phase Current Imbalance	<2%
Photovoltaic Interface	
Operating Voltage, Nominal, 20°C Ambient	335
Max Power Tracking Range	300-380
Max Open Circuit Voltage	600
Ripple Voltage, RMS	<1%
Performance	
Conversion Efficiency, 100% Output	>97%
25% -100% Output	>96%
Switching Frequency	20kHz
Standby Losses	<20W
Max Power Track Accuracy	+/- 1%
Auto Start Sense	Array Current
Auto Shutdown Sense	Pout<100W
Diagnostics/Fault Detect	Auto
Packaging/Environmental	
Dimensions	48" x 20" x 8"
Weight	150 lb.
Operating Temp, Ambient	-25°C to +45°C
Humidity	0-100%
Integrity, DC Interface	NEMA 12
Bridge/Control	NEMA 4
AC Interface	NEMA 3R
Cooling	External Forced Convection
Finish	Powder Coat, White
Noise	<50 dBA (Fans on)

General IPPU Specifications (Continued)

Disconnects

Contactors	DC, AC Load Break
DC Disconnect	Pullable Fuses (Deadfront)
AC Disconnect	3 Pole Circuit Breaker

Protection/Fault Detection

- Overtemperature - IGBT Junction Temp>100 deg C
- System Fault 1 - Undervoltage Control Power
- System Fault 2 - Output Current Imbalance>10%
- DC Ground Fault - Ground Current >2 Amps dc
- Synchronization Error - Loss of Phase Lock
- Overpower - Over Voltage DC Bus>400Vdc
- Overcurrent - Line Current>90 Amps Peak
- Frequency Fault** - Line Frequency>61.0 Hz or <58.5 Hz
- Utility Voltage Fault** - Vac>106% Nom or < 86% Nom

Design Standards

- 1996 NEC, UL 508, UL 1741

Front Panel Control (Local Disable Overrides Optional Remote Reset)

- Run
- Stop/Emergency Off/Disable
- Reset

Status Indicator, Front Panel

- Power Transfer (AC, DC Present)
- Standby (AC Present, Low DC Power)
- Shutdown (Reset Required)

LCD Front Panel Display Status/Instrumentation

- Standby: "STANDBY"
- Run: "PCU xx.x kWAC ...SCROLL...xx.x Vdc"
- Shutdown: "SHUTDOWN" (Fault display on control board)

Remote Control

- Disable - Remote Contact Closure (+5 vdc to +15 vdc)
- Reset - By Momentary Closure/Toggle of Disable Contact/Switch

* Maximum allowed line voltage to meet requirements of UL 1703 and provide maximum power tracking over the specified ambient temperature range.

** Field Testable by Signal Injection

Upon completion of the design of the IPPU sub-assemblies, and analysis of its functions, an enclosure was designed to integrate with UPG's tracker drive assembly for direct mounting to the sub-array structure in the field.

The output power rating of the IPPU was based upon the number of PV modules supported by UPG's existing single-axis solar tracking array structure. Although for future multi-megawatt PV power system a larger sub-array size may offer greater economies of scale, the IPPU and modular sub-array was initially to be rated at 20 kW ac. To meet the voltage requirements of UL Standard 1703 and the 1996 National Electrical Code, the rating of the IPPU/Sub-Array was derated to 15 kW ac.

Due to its complexity, UPG planned the development of the IPPU to proceed in three stages. First, an engineering prototype would be developed to allow preliminary factory and field testing and evaluation. Second, a production prototype version would be developed, fabricated, and subjected to exhaustive factory and field testing building upon the results of the engineering prototype. Third, a production version would be developed for commercial production incorporating all of the improvements learned from the production prototype version in addition to a number of other modifications to further reduce costs due to the higher expected quantity of production.

UPG fabricated one engineering prototype IPPU (sub-assemblies and enclosures) and subjected the sub-assemblies to a series of factory tests. As is to be expected with any complex high power electrical/electronic component, a number of problems were observed which are described below.

IGBT SWITCHING NOISE EFFECTING OUTPUT REGULATION

Upon completion of preliminary sub-assembly testing, the first engineering prototype IPPU was assembled and quickly became operational in the grid-tied configuration. The sine wave current output, however, was not stable at over 30% of full power and at higher power levels, Insulated Gate Bipolar Transistor (IGBT) failures occurred. UPG's analysis of possible problems, at that time, indicated current feedback loop instability, common mode noise injection, radiated noise pickup, opto isolator dV/dT failure, and/or induced noise on the ribbon cables. A number of remedies were attempted including taking active gain-phase measurements, changing error amp frequency compensation, switching to bang-bang regulation, shielding cables, rerouting grounds, installing fiber optic drives, and shielding bridge components, but only minor improvements were obtained. A time consuming separation and redesign of the regulator portion of the bridge board with the addition of a ground plane layer finally solved the problem. Subsequent revisions of the bridge board will reintegrate the bridge and regulator functions by incorporating lessons learned.

OVERSHOOT ON THE DC BUS

The inverter utilizes ultra fast IGBTs in the bridge design with current fall times on the same order (160nS) as Field Effect Transistors (FET). The parasitic dc bus inductance and bus capacitance equivalent series reactance as seen by the IGBT must be very low or the IGBT maximum voltage rating will be exceeded by the voltage overshoot. Initial measurements of the bus overshoot were performed with a Tektronix 2220 60MHz digital oscilloscope and the overshoot, as measured, was within design limits. Unfortunately, IGBTs continued to fail at high power levels. It was decided to put resistor-capacitor-diode (RCD) snubbers across each switching device with the intent to limit turn-off dI/dT. To optimize the snubber design, a Fluke PM3394A, 200Mhz digital scope was obtained, and it revealed that the voltage overshoot was three times the amplitude as measured with the slower Tektronix equipment. The overshoot was determined to be responsible for the failing devices and not excessive dI/dT as originally concluded. Installation of optimized resistor-capacitor (RC) snubbers to damp the overshoot solved the problem and allowed the inverter to operate at full power. Unfortunately, the addition of the snubbers reduced the conversion efficiency by one full percentage point. The bridge board parasitic inductance components have been identified and the next revision of the bridge PCB layout should significantly reduce the losses associated with addition of the snubbers.

CONTROL BOARD NUISANCE FAULTS

Factory testing revealed a problem with nuisance faults upon system start-up which caused the system to randomly trip off. Numerous attempts to solve this problem were made including slowing down faults which had non-critical response times, suppressing ac and dc contactor transients, and reworking the input impedance's into the fault multiplexer, yet were met with little success. The problem was eventually solved by holding off all faults (except the critical line overcurrent and overvoltage bus faults) for 50mS following the run command, allowing the contactors to settle mechanically before the faults were enabled.

THERMAL

A significant problem relates to thermal management. It became evident that the thermal resistance in the critical path from IGBT junction to ambient was greater than the original design calculations had shown. Compounding the problem was the addition of heat associated with the previously described snubber losses. The short term solution to this problem is believed to be the addition of an external fan shroud and two small DC fans (6W each). Although for enhanced reliability and reduced maintenance, the original IPPU design concept rejected active cooling components such as fans, this modification will allow IPPU operation at full power in 113° F ambient temperatures with some margin. The long term solution is to perfect a method of soldering the TO-247 IGBT cases to the heat spreader block, reduce snubber losses with a new bridge board layout, change the material type and/or thickness of the heat spreader plate, and install a sun shield to prevent additional heatsink temperature rise from the sun. One of the Year Two objectives includes a return to the original concept of natural convection cooling.

TRACKER CONTROL MICROCONTROLLER

The "Solartrak" array tracker controller circuitry utilized by UPG was originally designed by Alex Maish at Sandia National Laboratories for use in single and two-axis solar tracking systems without real time rotational feedback. UPG's first effort at integrating the "Solartrak" into the IPPU was to use a potentiometer and pendulum configuration to provide the feedback signal. The software/firmware changes, technology transfer and debugging were somewhat problematic but with assistance from Mr. Maish and Sandia, the array position tracker became operational. A backlash problem remains with the rotational sensor which may effect long term reliability, and this problem will be addressed during Year Two.

Based upon the results of the first engineering prototype, UPG fabricated an additional eight (8) engineering prototype IPPU's for delivery under a PV power systems contract from the Sacramento Municipal Utility District. A preliminary manufacturing plan was developed and delivered to NREL after fabricating these eight prototypes and a set of evaluation criteria was created to facilitate the selection of a possible future organization to manufacture volume quanities of the IPPU. It was determined that for the near term all IPPU's would be assembled by UPG in our San Luis Obispo, California facility utilizing sub-assemblies designed and specified by UPG and produced by outside vendors. These IPPU's were installed during July, 1996 and testing and evaluation of these units is ongoing. There is no substitute for field testing of PV system components in terms of identifying weak areas of design. Parallel operation of grid connected inverters requires particular attention and a number of circuit modifications were required to mitigate problems encountered.

RESULTS

In Year One of this two year PVMaT Phase 4A1 work effort, UPG completed the design, fabrication, and installation of a modular and integrated 15 kW ac solar tracking PV power system sub-array which exceeded UPG's 20% cost reduction goal. The sub-array utilizes twenty-eight (28) 11M55 Modular Panels and one (1) engineering prototype IPPU. Eight (8) such sub-arrays were supplied to the Sacramento Municipal Utility District (SMUD) and UPG is continuing to evaluate their performance.

PV power systems provided to SMUD and other UPG customers which utilize the Modular Panels and Integrated Power Processing Units developed under this Phase 4A1 sub-contract not only serve as field test sites for the new technologies but also demonstrate through competitive bidding processes the cost savings inherent in their design.

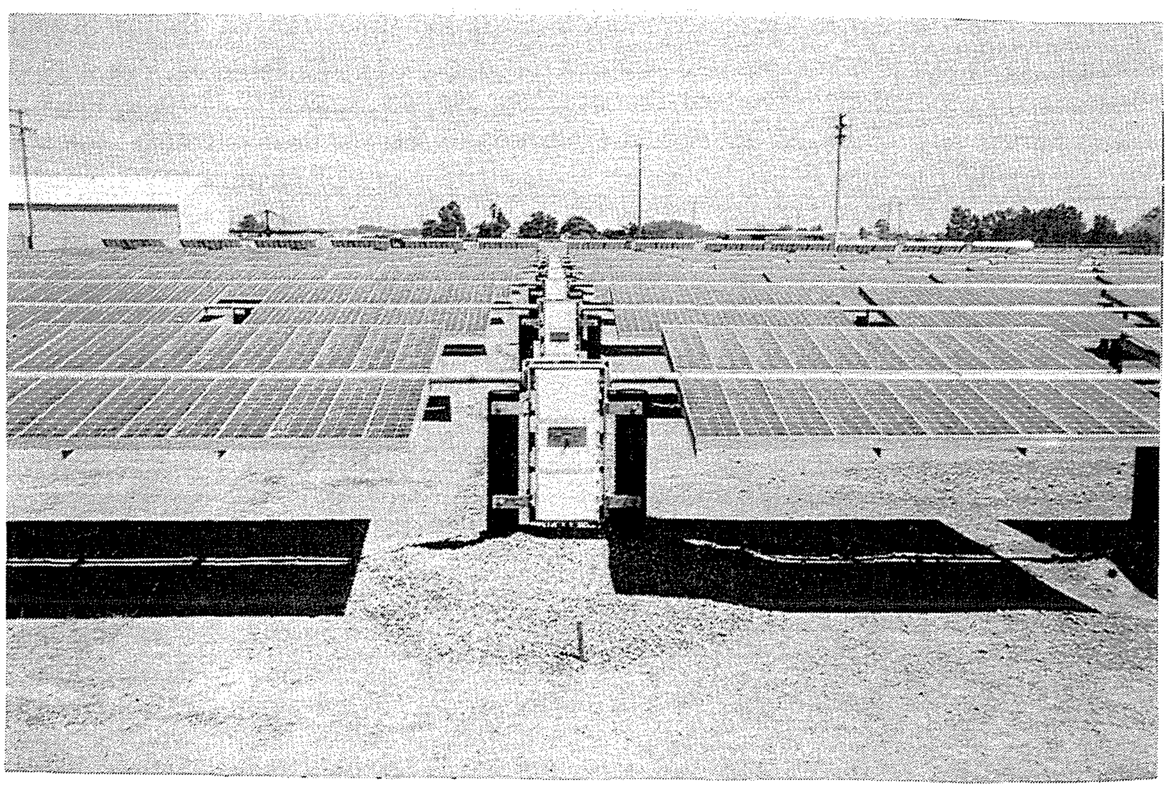

Figure 8. Prototype sub-arrays in Sacramento, California.

Figure 9 compares the major field tasks required to design and install a nominal 100 kW grid connected PV power system before and after the development of UPG's integrated sub-array concept. The reduction in the number of discrete installation tasks of almost 50% indicates the extent of BOS cost reduction. In addition, reduced field labor typically translates into higher installed PV system quality, and a reduced component count typically results in greater PV system reliability.

	MAJOR FIELD TASKS: Before Integrated Sub-Array Development		MAJOR FIELD TASKS: After Integrated Sub-Array Development
1	Electrical Design	1	Modular Design Package
2	Mechanical and Structural Design	2	Site Mobilization
3	Site Mobilization	3	Site Preparation
4	Site Preparation	4	Support Pole Hole Augering
5	Support Pole Hole Augering	5	Support Pole Installation
6	Support Pole Installation	6	Drill Tracker Drive Assembly Mounting Holes
7	Install Conduit Junction Boxes	7	Drill Torque Tube Bearing Plate Mounting Holes
8	Install AC Tracker Motor Junction Boxes	8	Install Torque Tube Bearing Plates
9	Conduit Trenching	9	Install IPPU Assemblies
10	Electrical Equipment Concrete Pad Excavation	10	Conduit Trenching
11	Electrical Equipment Concrete Pad Form	11	Lay Conduit
12	Lay Conduit	12	Set Pre-Cast Transformer Pad and Transformer
13	Backfill and Compact Conduit Trenches	13	Pull Conduit and Torque Tube Wires
14	Pour Concrete Electrical Equipment Pad	14	Backfill and Compact Conduit Trenches
15	Drill Torque Tube Bearing Plate Mounting Holes	15	Install Torque Tubes
16	Drill Tracker Drive Assembly Mounting Holes	16	Install PV Panels
17	Install Torque Tube Bearing Plates	17	Connect All Wires
18	Install Tracker Drive Assemblies	18	Test IPPU's
19	Install Torque Tubes	19	Array Start-Up
20	Install Struts	20	
21	Install PV Module Rails	21	
22	Install PV Modules	22	
23	Install Row Junction Boxes	23	
24	Install Tracker Limit Switch Junction Boxes	24	
25	Install Inverter	25	
26	Install Transformer	26	
27	Install DC Interface Enclosures	27	
28	Install Tracker Drive Control Enclosure	28	
29	Wire PV Modules	29	
30	Pull Conduit and Torque Tube Wires	30	
31	Connect All Wires	31	
32	Test Source Circuits	32	
33	Test Sub-Arrays	33	
34	Test Inverter	34	
35	Test Tracker Controller and Tracker Motors	35	
36	System Start-Up	36	

Figure 9. PV power system field installation tasks.

The following key design areas were responsible for most of the Year One cost reductions quantified in Figure 10:

- Integration of seven discrete electrical enclosures into a single multi-functional power processing unit.
- Elimination of extruded aluminum frames on each PV module.
- Simplification of panel support structure.
- Replacement of 4-pack module shipping boxes with reusable/recyclable 8-pack shipping boxes.
- Substitution of factory labor for field labor in the assembly of PV panels.
- UL listing of UPG's 11M55 PV panel

MAJOR PV SYSTEM COST GROUP	% OF TOTAL PV SYSTEM COST PRE-PVMaT	PVMaT YEAR ONE PV SYSTEM COST REDUCTION	NET PVMaT YEAR ONE PV SYSTEM COST REDUCTION
PV MODULES	60%	5%	3%
AREA RELATED BOS	25%	43%	10.7%
POWER RELATED BOS	15%	51%	7.6%
TOTAL NET PV SYSTEM COST REDUCTION			21.3%

Figure 10. Year One system cost reduction results.

During Year Two, UPG will develop improved versions of both the Modular Panel and IPPU to obtain an additional 10% reduction in the cost of PV power systems. A portion of this cost reduction will be derived from UPG's use of printed circuit boards as the foundation for all IPPU sub-assemblies. The existence of many outside contract manufacturing companies specializing in high throughput insertion and interconnection of printed circuit board components will permit UPG to focus on sub-assembly level testing and final IPPU assembly tasks. In this manner, UPG's present facilities and staff will be able to produce over 200 IPPUs per year, representing over 3 MW of PV power systems. Additionally, these results enable UPG to project the capability to scale up production of all BOS components to a level of 100 MW/year within a twelve month period. The fundamental conclusion to be drawn from UPG's PVMaT BOS development effort is that the cost and availability of BOS components will not be a limiting factor in the widespread commercialization of photovoltaic technology.

ACKNOWLEDGMENT

The authors wish to acknowledge the role of the U.S. Department of Energy in the support of NREL's PVMaT Program, Sandia's BOS Program, and PV COMPACT's UPVG TEAM-UP Program without which the development, demonstration, and commercialization of UPG's low-cost integrated sub-array would not have been possible. In particular, the authors appreciate the support and guidance provided by the NREL/SNL Technical Monitoring Team consisting of H. P. Thomas (NREL), B. D. Kroposki (NREL), and W. Bower (SNL).

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1997	Annual Technical Report, 11 July 1995 - 31 July 1996

4. TITLE AND SUBTITLE

Development of a Low-Cost Integrated 20-kW ac Solar Tracking Sub-Array for Grid-Connected PV Power System Applications; Phase I Annual Technical Report, 11 July 1995 - 31 July 1996

5. FUNDING NUMBERS

C: ZAF-5-14271-06
TA: PV705101

6. AUTHOR(S)

M. Stern, R. West, G. Fourer, W. Whalen, M. Van Loo, and G. Duran

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Utility Power Group
9410 G DeSoto Ave.
Chatsworth, CA 91311

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SR-520-23118

DE97050806

11. SUPPLEMENTARY NOTES

NREL Technical Monitor: H. Thomas

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

UC-1280

13. ABSTRACT (Maximum 200 words)

This report describes work done in the first year of this 2-year Photovoltaic Manufacturing Technology (PVMaT) Phase 4A1 project, in which Utility Power Group (UPG) successfully completed the design, fabrication, testing, and demonstration of a modular and integrated 20-kW ac solar-tracking PV power system sub-array. The two key components developed are a modular panel that optimizes factory assembly of PV modules into a large-area, field-deployable, structurally integrated PV panel, and an integrated power-processing system that combines all dc and ac power collection, conversion, and control functions within a single field-deployable, structurally integrated electrical enclosure. UPG exceeded its goal of providing a 40% reduction in area-related balance-of-systems (BOS) costs and a 50% reduction in power-related BOS costs by achieving cost reductions of 43% and 51%, respectively. The net reduction in the total cost of single-axis, solar-tracking, grid-connected PV power systems achieved by UPG was 21.3%. This result changes the previous typical allocation of total system cost from 60% PV modules and 40% BOS to a new allocation of 72% PV modules and 28% BOS. Notwithstanding required improvements in reliability and performance, UPG concludes that BOS costs are no longer an obstacle to the widespread commercialization of PV technology in grid-connected applications when the UPG system approach is applied.

14. TERMS

photovoltaics ; Photovoltaics Manufacturing Technology ; PVMaT ; grid-connected photovoltaics ; solar-tracking PV power system sub-arrays ; balance of systems

15. NUMBER OF PAGES
29

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL