SUBSYSTEM ENGINEERING AND DEVELOPMENT OF GRID-CONNECTED
PHOTOVOLTAIC SYSTEMS*

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Summary

The experience gained in fielding residential and intermediate-sized photovoltaic application experiments is summarized. This experience is used to guide the engineering and development of array and power conditioning subsystems for grid-connected photovoltaic systems. A major consideration in this development effort is cost. Through innovative engineering, using a modular building block approach for the array subsystem, it is now possible to construct array fields, in moderate quantities, for about \$52/m² excluding the photovoltaic modules. Similarly, results of power conditioning subsystem development indicate a projected cost of about \$0.25/W_p for advanced units with conversion efficiencies in excess of 90%.

1. INTRODUCTION

The major emphasis of the U.S. Department of Energy's photovoltaic (PV) program has been on the development of grid-connected systems. The worth of a PV system, in this scenario, is measured by how well the levelized energy cost competes with the cost of conventional grid-supplied energy. For this reason, effort has been placed on reducing cost, particularly for the PV modules. In the last couple of years, increasing attention has been given to cost and performance considerations of the balance-of-system (BOS) element, i.e., the non-photovoltaic part of the system.

The major system elements are the array and power conditioning subsystems. The array subsystem incorporates all hardware necessary to deliver unregulated dc power to the power conditioning subsystem and typically includes, in addition to the PV modules, array field area-related items such as land, structures, foundations, field wiring, electrical subsystem protection, and site preparation. The power conditioning subsystem includes the equipment necessary to regulate dc power, convert it to ac power, and deliver it to a distribution grid. This involves all the hardware needed to interface with the array and the utility, as well as power conversion and control.

Considerable experience has been gained with these subsystems through the fielding of full-scale PV system experiments. Detailed performance and cost analyses of the various system components have been performed and the results used to guide subsystem engineering and development efforts. This paper summarizes this experience and the resultant advances in subsystem performance and cost.

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*This work was supported by the U.S. Department of Energy Division of Photovoltaic Energy Systems Technology.

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2. PHOTOVOLTAIC SYSTEM EXPERIMENTS

The U.S. PV program has fielded a number of intermediate-sized systems over the past five years. The oldest of these is an irrigation application in Mead, Nebraska. That system, a 25 kW_p flat-plate array, became operational in July 1977. It has operated reasonably trouble-free but is beginning to experience some PV module degradation due to cell interconnect failures. More recently, other intermediate-sized experiments have been planned and constructed or are in the process of being implemented. These experiments are listed in Table I along with characteristics of each system. More details of several of these systems are given elsewhere (1).

TABLE I. U.S. INTERMEDIATE-SIZED PV SYSTEMS

APPLICATION	LOCATION	SIZE (kW)	ARRAY TYPE	INITIAL OPERATION	COST (\$/W)
OFFICE BLDG.	ALBUQUERQUE	47	PARABOLIC TR.	MAY 82	30
HIGH SCHOOL	BEVERLY, MA	96	FLAT-PLATE	JAN 81	30
AIRPORT	DALLAS, TX	27	LIN. FRESNEL	JUN 82	42
HOSPITAL	KAUAI, HI	35	PARABOLIC TR.	JAN 82	51
SHOPPING CENTER	LOV'TON, NM	100	FLAT-PLATE	MAR 81	29
UPS INVERTER	EL PASO, TX	16	FLAT-PLATE	JAN 81	30
LIGHT MFG.	SAN BERNARDINO	35	FLAT-PLATE	JAN 82	23
MUSEUM	OKLA. CITY	135	FLAT-PLATE	FEB 82	21
AIRPORT	PHOENIX, AZ	225	PT. FRESNEL	JUN 82	18
IRRIGATION	MEAD, NB	25	FLAT-PLATE	JUL 77	28
NAT. PARK	UTAH	100	FLAT-PLATE	JUN 80	31
RADIO STATION	BRYAN, OH	15	FLAT-PLATE	AUG 79	20
RADAR STATION	MT. LAG., CA	60	FLAT-PLATE	JUN 79	22
COMMUNITY COLLEGE	B'VILLE, AR	240	PARABOLIC TR.	MAY 81	30
UNIVERSITY	WASH., DC	300	FLAT-PLATE	SEP 84	21
UTILITY	SACRAMENTO	1000	TBD	JUN 84	12

An application receiving increased attention within the last two years is private residences. Because of concerns about safety, much of the experimentation in the U.S. has been in residential experiment stations (RES). The concept of a RES is to implement a number of prototype PV systems on simulated houses in a controlled-access test facility. Two such RES's have been implemented and a third will be implemented this year. Not all experimentation with these small roof-mounted systems has been restricted to the RES's. Seven other systems have been constructed. The U.S. PV program residential activity is summarized in Table II.

TABLE II. U.S. RESIDENTIAL PV SYSTEMS

PROJECT	LOCATION	NUMBER SYSTEMS	SYSTEM SIZE (kW)	INITIAL OPERATION	COST (\$/W)
NE RES	CONCORD, MA	5	5.7	NOV 80	25
SW RES	LAS CRUCES, NM	8	5.4	MAR 81	23
CARLISLE	CARLISLE, MA	1	7.8	FEB 81	14
FSEC	CAPE CAN., FL	1	4.0	AUG 80	-
HI HOUSES	HAWAII	3	3.3	MAY 81	29
LONG HOUSE	PHOENIX, AZ	1	6.6	MAY 80	39
UNIV. TEX.	ARLINGTON, TX	1	8.0	OCT 78	21
SE RES	TBD	TBD	TBD	83	-

These two large experimental sets have provided a very significant data base from which to assess system performance and to highlight areas which dominate system cost. In the remainder of this section a summary is presented of the lessons learned which deal with the two major subsystems, i.e., the array and power conditioning.

Systems incorporating concentrator PV arrays are just now becoming operational. For this reason, most of the discussion here will deal with the flat-plate systems. The costs for six flat-plate, intermediate-sized systems have been discussed in detail in a paper by Burgess and Biringer (2). The data in Table III are taken from that paper.

TABLE III. PV SYSTEM COST BY COST CATEGORY

PROJECT	UPS		SHOP. CTR.		HIGH SCH.		MUSEUM	
COST CATEGORY	\$/m ²	\$/W	\$/m ²	\$/W	\$/m ²	\$/W	\$/m ²	\$/W
ENGINEERING	593	10.56	560	8.41	495	7.42	373	3.06
PV MODULES	576	10.23	753	11.32	725	10.86	1435	11.77
STRUCTURE	90	1.60	44	0.66	46	0.69	277	2.27
FOUNDATION	18	0.32	70	1.05	121	1.81	84	0.69
CIVIL WORK	54	0.96	137	2.05	178	2.67	195	1.60
ELECTRICAL	219	3.91	173	2.59	231	3.46	104	0.85
PCS	108	1.91	180	2.70	159	2.38	56	0.46
BUILDINGS	54	0.96	38	0.57	20	0.29	—	—
TOTAL	1712	30.45	1955	29.35	1975	29.58	2524	20.70

As shown, the costs for design can run as high as 30-35% of the total project, the PV modules represent about one-third of the cost, and the remaining cost is for the BOS elements. Analysis of this data and the system design details has highlighted the following reasons for the high costs in the design and BOS categories.

- All the designs were developed essentially independent of each other, yet much similarity exists. This suggests that standardized designs are applicable and that considerable cost savings are possible if they were available.
- Structures and foundations were designed according to standard A & E practices which incorporate large "margins-of-safety". The resultant costs of \$2-4/W_p are not acceptable. More innovative approaches are necessary and some margins-of-safety will have to be sacrificed. Because of the conservativeness of the present designs (e.g., 2-3 times over-design on wind loading), this is possible without sacrificing personnel safety.
- Site preparation has tended to be overdone in order to obtain perfectly level sites and aesthetically pleasing results. This has been the practice because of the experimental nature of the projects and the large number of visitors expected at the sites. In actual applications, "favorable" sites (i.e., reasonably level, no rock outcroppings, and minimum vegetation) should be selected and very little site preparation performed.
- Electrical wiring costs have frequently exceeded the total allowed system cost. As in the case of structures and foundations, standard A & E practices have been applied in electrical wiring design.

Numerous junction boxes, interconnections, and conduit have been incorporated. Innovative approaches to electrical wiring are required, eliminating essentially all of the junction boxes.

The next section discusses how many of these features and lessons learned have been incorporated into standardized, modular building block array subsystems for ground-mounted arrays.

Four types of mounting techniques have been examined for small roof-mounted systems: standoff, direct, integral and rack mounts. The evaluation of these mounting techniques is still in progress; however, some preliminary results are available. These include:

- Standoff mounts are adaptable to retrofits and the array operates at an acceptable temperature.
- Direct mounts are also adaptable to retrofits but the array operates at a temperature 10-20°C higher than arrays in the other mounting schemes. This is due to cooling from one side of the module only.
- Integral mounts are potentially less expensive since the array is the major roof element and roofing credit can be applied to the array cost. Operating temperature is not a problem since innovative schemes for cooling the underside have been developed.
- The rack mount is simple but adaptable only to flat-roof houses.

More details of new array mounting techniques are discussed by Ross (3).

The lessons learned regarding intermediate-size power conditioning subsystems can be classified into two major categories: 1) excessive cost for the adapted uninterruptible power supply inverters and 2) problems with both the array and utility interfaces. These are discussed in a later section.

3. ARRAY SUBSYSTEM DEVELOPMENT

Array subsystems have been the focal point of extensive development activities within the U.S. PV program, primarily as a result of the lessons learned through system experiments and other system definition activities. Recent studies have examined cost reduction in array subsystems for ground-mounted systems through component integration, array field design optimization, and detailed installation analyses (4). Similar activities have emphasized the development of integrated and optimized roof-mounted arrays for residential systems (5). This latter work is detailed by Ross (3) and will not be covered here. The remaining discussions on array subsystem development will concentrate on medium- and large-size systems, primarily commercial/industrial type applications, and will highlight the development of modular, low-cost array field designs.

3.1 Cost Reduction

The ideal approach toward low-cost array field subsystem development is to examine actual costs and installation experience for operating systems and to identify areas where cost reductions can be made. This has been done for the Lea County Electric Cooperative application experiment,

typical of a medium-size, ground-mounted, flat-panel system. This system (identified as a shopping center application in Tables I and III) has a nominal power output of 100 kW and includes 1503 m² of collector area. As shown in Table IV, specific items were examined for potential cost reduction. The proposed activities which were identified are based on detailed evaluation of the major cost drivers for each subsystem.

TABLE IV. MAJOR ARRAY FIELD ITEMS REQUIRING COST REDUCTION

ITEM	LEA CO. SHOPPING CENTER COST	COST REDUCTION ACTIVITY
ARRAY FIELD ENG. DESIGN	\$2.58/W	DEVELOP STANDARDIZED ARRAY FIELD DESIGNS AND BUILDING BLOCK HARDWARE; MINIMIZE SITE SPECIFIC DESIGN WORK
SITE PREPARATION	\$137/m ²	SELECT SITES WITH FAVORABLE CON- DITIONS (MINIMAL CLEARING AND EXCAVATION WORK)
STRUCTURAL SUBSYS.	\$114/m ²	USE LOW-COST FOUNDATIONS; DEVELOP INTEGRATED PANEL/STRUCTURE HARDWARE; USE SIMPLIFIED MECHANICAL ATTACHMENT; MAXIMIZE FACTORY PANEL ASSEMBLY
ELECTRICAL SUBSYS.	\$173/m ²	DEVELOP INTEGRATED FIELD WIRING; MINIMIZE SUBARRAY JUNCTION BOX INSTAL- LATION; USE DIRECT-BURIAL AND LOW-COST MODULE WIRING CONNECTORS; MINIMIZE INSTRUMENTATION

A key element for cost reduction is the development of standardized array field designs and component hardware. Estimates of the site specific costs for the application experiment systems noted earlier range from 30 to 35 percent of the total project costs. Standardized designs should significantly reduce the site specific or custom design work as well as reduce the engineering costs (system design, A & E fees, construction management) associated with future installations.

The poured concrete slab foundations represent 60 percent of the Lea County project structural costs. Integrated panel/structure hardware coupled with low-cost foundations were identified as cost-effective options. Similarly, the design approach for these structures should adopt a philosophy of being operational at reasonable environmental loads and remain safe, although allowing structural yielding and deformation, at survival condition loads.

Site preparation costs for the Lea County project were driven by excavation and backfill operations, representing 33 percent of the total costs, and the use of stone ground cover to control dust and weeds at a cost fraction of 23 percent. To reduce these costs, site selection should be restricted to locations which require minimal clearing and excavation. Leveling requirements should be minimized, through innovative foundation design, and lower-cost options, such as gravel instead of stone, should be incorporated in site plans.

Subarray conduit and junction box costs dominate the Lea County electrical subsystem costs, representing 45 percent of the total cost. Integrated field wiring designs incorporating direct-burial cabling, few if any junction boxes, low-cost module interconnection, and minimal instrumentation were identified for cost reduction options. Similarly, lightning protection should consist of terminal protection devices (to limit transients at the array and power conditioning equipment) and

protective shielding for long cable runs. Direct strike protection should be considered only for areas with high thunderstorm activity where favorable risk/cost benefits so warrant.

3.2 Modular Array Field Designs

To significantly reduce array field costs, Sandia National Laboratories through two contractors, Battelle-Columbus Laboratories and Hughes Aircraft Company, has designed and developed totally integrated, modular array field designs for flat-plate systems which implement the cost reduction options noted previously (6,7). These designs, which are proposed for system sizes ranging from 20 to 500 kW, are presented in detail elsewhere (8). Based on estimated array field BOS costs (1980\$) including site preparation, structural subsystems, and electrical subsystems, the Battelle design and Hughes design are projected at \$51.93/m² and \$62.92/m², respectively, for low production quantities and favorable installation sites. Complete engineering drawing packages, including detailed construction specifications, are available for each design.

The development of modular array field designs incorporating concentrator arrays should be completed by June of this year. These designs utilize two state-of-the-art concentrating collector arrays. The first is a point-focus, fresnel-lens array using a center-post mount. The second is a line-focus, fresnel-lens module mounted in an end-supported frame. Both systems are passively cooled and use two-axis tracking. These designs will be detailed in engineering drawing packages with example layouts for for 20-, 100-, and 500-kW array fields.

3.3 Other Development Activities

Other key activities for medium- and large-size systems include the following:

- Electrical Subsystem Optimization
- Integrated Structure Design
- Automated Installation Methods
- System Grounding and Fault Protection Study

The subsystem optimization work examined the effects of array characteristics, system power, and voltage levels, as well as other design and application specific factors on first and operating costs for large (0.5 to 1000 MW_p) PV power systems (9). The complete electrical subsystem including dc wiring, ac wiring, grounding, and transient surge protection was addressed. A key result of this work is that array subfields with size and voltage ratings of 5 MW and 2000 Vdc, respectively, appear optimum for the combined costs of dc wiring and power conditioning equipment.

Bechtel Group, Inc., through the integrated structure design work, has developed an optimized design incorporating PV modules into a structurally integrated panel assembly. The projected cost (1980\$) for the installed structural subsystem is \$31/m² of collector area. This structural design was included in the automated installation methods work conducted by Burt Hill Kosar Rittelmann Associates (10). Installation scenarios, both conventional and automated, were developed for large photovoltaic array fields as part of a comprehensive study of installation methods. Results for a 10-MW flat-panel array field, installed using conventional methods at a southwestern U.S. location, show a projected installation cost (including overhead and profit) of \$28/m² of collector

area. This projection includes all the site preparation (roads, fencing, drainage), electrical subsystems, and foundation costs. Adding in the cost of the panel developed by Bechtel gives a total installed cost (1980\$) of approximately \$50/m². It is estimated that installation costs can be reduced by approximately \$11/m² by using an appropriate mix of automated and conventional installation methods. Preliminary designs for the required robotic equipment, using currently available component hardware, have been prepared.

The last activity, system grounding and fault protection study, is focused on a design manual to be published during 1983.

4. POWER CONDITIONING DEVELOPMENT

The role of the power conditioner in a grid-connected PV system goes beyond dc to ac inversion. Other critical functions include interfacing the array to the inverter and the inverter to the utility line as well as providing overall system control and protection. As depicted in Fig. 1, there are four major functions of a power conditioning subsystem (PCS).

FIG. 1 - ROLE OF PCS IN GRID-CONNECTED PV SYSTEM

In most PV system application experiments the major PCS performance problems have been related to interfacing and control functions. On the dc-side, PV unique source characteristics such as high array V_{OC} and a limited I_{SC} have created early morning and late afternoon start-up problems. Periods of low array power output have lead to excessive on/off cycling of some inverters. As a synchronous ac power source on the utility-grid, the PCS has been exposed to line-voltage fluctuations and temporal phase shifting. Such transients have required special attention in the design of PCS power flow controls and protection schemes.

Another design constraint experienced by the grid-connected PCS is the power quality requirement imposed by the local utility company. At the present time, there is no technical precedence for connecting a large number of inverter sources into the utility grid. Therefore, requirements have varied from site to site.

4.1 Current Activities

Field experience has pointed out several complex issues in the PCS interfacing and controlling functions. A summary of these issues and other technical concerns surrounding the PCS is provided in Table V.

TABLE V. TECHNICAL ISSUES SURROUNDING THE GRID-CONNECTED PCS

ARRAY INTERFACE	PCS HARDWARE DEVELOPMENT	UTILITY INTERFACE
<ul style="list-style-type: none"> • POWER TRACKING • Vdc MATCHING • POWER LIMIT • Vdc TOLERANCE • PROTECTION • USER SAFETY • ON/OFF CYCLING 	<ul style="list-style-type: none"> • PERFORMANCE • EFFICIENCY • RELIABILITY • MAINTAINABILITY • SURVIVABILITY • EMI & ACOUSTICAL COMPATIBILITY 	<ul style="list-style-type: none"> • POWER FACTOR • HARMONICS • STABILITY • LINESMAN SAFETY • PROTECTION • CONTROL • ISOLATION X'FORMER

REQUIREMENTS FOR THE PCS IN A PV SYSTEM

- IN-SITU TESTING AND EVALUATION
- CODES AND STANDARDS
- GROUNDING
- DESIGN CRITERIA/PCS SIZING

Using typical cell models, weather tapes, and a computer applied algorithm, the array interface has been characterized from the point-of-view of the PCS. These data give the potential PCS manufacturer an estimated percent of annual array energy loss for several power-tracking approaches from fixed voltage to a full-range input voltage tracking window. Also provided are array voltage and current levels under extremes of operation and a plot of the annual power vs hours profile of array output. These array data allow the PCS manufacturer to make array interface design "tradeoffs" that maximize the ac energy output of the PV system.

Research in the area of optimum power conversion has suggested abandoning very small (100 W) distributed parallel inverter schemes. The major drawbacks were inefficient use of magnetic materials, high total part count and low efficiency projections. An approach at the 4 kW level, which is considered to be close to optimum, shapes half-sine waves in a single-quadrant, push-pull buck converter with alternate halves inverted with a transistor bridge. This prototype has performed well in a breadboard stage.

Consensus utility interface requirements currently used for a residential PCS are: low harmonic distortion (5% current THD into a linear load) and nearly unity power factor (.95 lagging to .95 leading from 1/8 to full load). Also an isolation transformer is required between the utility and the PV system. Examples of on-going research intended to determine long-term utility connection requirements are; dynamic simulations of dispersed PV at varying penetration levels, power factor and harmonic effects on the distribution feeder, and identification of requirements for transformerless systems.

With respect to future safety codes, wiring and grounding standards, two documents have been drafted. One sets forth safety standards for residential power conditioning units (11). The other covers special grounding and wiring requirements of PV systems (12).

PCS specifications are being developed to improve technical communication with industry. For example, a residential baseline specification prepared for single-phase, 2-10 kW power conditioners (13) includes:

- Photovoltaic array output characterizations for flat-plate modules
- Protection, efficiency, and other performance requirements
- Latest available consensus utility interface requirements
- Recommended test procedures

This information allows the designer to optimize ac energy output of the PCS within known performance and interface constraints.

Small power conditioners are presently available that will meet the specifications in (13). Table VI provides cost and efficiency details for inverters that have operated in the U.S. DOE residential experiments.

TABLE VI. PCS CANDIDATES EXPECTED TO MEET OR EXCEED THE RESIDENTIAL BASELINE SPECIFICATION

AVAILABLE MFG./MODEL	OUTPUT RATING	EFFICIENCY (100%)	OPERATING PRINCIPLE	POWER TRACKER	PRICE (\$/W)
WINDWORKS/GEMNI WITH FILTER	4kW 8kW	92* 92*	LINE COMM., CUR. SOURCED, SCR BRIDGE (120 Hz) WITH WAVESHAPING FILTER	N/A	- 0.94*
ABACUS CONTROLS/ SUNVERTER	4kW 6kW 10kW	91* 88 92*	SELF OSCILLATING, VOLTAGE SOURCED, X-SISTER BRIDGE (1.44 kHz) WITH PRE PRO- GRAMMED SINE WAVE IN PROM	PILOT CELL	1.59* 2.04 0.98*
HELIONETICS INC. (DECC)/61289 SERIES (2-12kW)	5kW 6kW 8kW	91* 91 91	SELF OSCILLATING OR LINE SYNC, VOLTAGE SOURCED X-SISTER BRIDGE WITH PULSE DURATION MODULATION CLASS "D" AMP (28 kHz)	PERTURB/ OBSERVE	1.00* 1.63 1.50
AMERICAN POWER CONVERSION CORP. SUNSHINE VI-2000& 4000	2kW 4kW	92 92*	SELF OSC. (LINE SYNC) CURRENT SOURCED PWM WAVESHAPING HF FRONT-END DOWN CONV. (13-20 kHz)	PERTURB/ OBSERVE	1.99 1.25*

* PROJECTED BASED ON DETAILED ANALYSES OR BREADBOARD TESTS OF PREPRODUCTION PROTOTYPE

Several 3-phase PCS units (20-200 kW) have also been built for the intermediate PV experiments. Most use a conventional modified Uninterruptible Power System technology (e.g. self-oscillating, voltage sourced, 6 or 12 step wave synthesis with output harmonic filtering). Another design used is a 3-phase line-commutated unit with appropriate output filtering and power factor correction. Neither of these approaches are considered promising in the long run. Price experience in this size range has been \$0.50-2.50/W.

4.2 Future Plans

Seven studies were recently completed (14) that identify promising conceptual designs in the 2-10 kW and 20-200 kW size range. Single and 3-phase advanced prototype hardware will be developed during the next 18 months using the baseline performance requirements as a guide. Anticipated results include greater than 91% efficiency and future selling prices in the \$0.20-0.30/W range for production levels of 1000 units/yr.

Another development activity in the near future will optimize a single-phase transformerless design based on anticipated future grounding, safety and utility interface requirements for residential PV systems. A 2% increase in efficiency over the 60 Hz isolation transformer approach is contemplated. Three promising advanced conceptual designs that have been identified for a 3-phase, 20-200 kW PCS include; a self-oscillating parallel transistor bridge (with advanced switching module), a line-commutated 6-pulse SCR step-wave synthesis (with complimentary parallel VAR inverter), and a hybrid, line/forced commutated 6-pulse multipattern programmed wave (with GTO commutated SCR for low-cost and high-efficiency). The projected efficiency range for these approaches is 93-96%.

5. CONCLUSIONS

Subsystem development activities have been implemented which lead to low-cost BOS. Array subsystem costs are now projected to be approximately \$52/m² for modular array field designs, a factor of 5-8 below current field experience. Similarly, the PCS is projected at \$0.25/W_p for medium-sized units in large production quantities. For a system with 10% conversion efficiency, these projections result in a BOS contribution of \$0.77/W_p toward the overall system cost.

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