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OPTIMIZED LOW-COST-ARRAY FIELD DESIGNS
FOR PHOTOVOLTAIC SYSTEMS*

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ABSTRACT

As manager of the U.S. Department of Energy Photovoltaic Systems Definition Project, Sandia National Laboratories is engaged in a comprehensive program to define and develop array field subsystems which can achieve the lowest possible lifecycle costs. This paper describes the major activity of this program, namely, the design and development of optimized, modular array fields for photovoltaic (PV) systems. As part of this activity, design criteria and performance requirements for specific array subsystems including support structures, foundations, intermodule connections, field wiring, lightning protection, system grounding, site preparation, and monitoring and control have been defined and evaluated. Similarly, fully integrated flat-panel array field designs, optimized for lowest lifecycle costs, have been developed for system sizes ranging from 20 to 500 kW_p. Key features, subsystem requirements, and projected costs for these array field designs are presented and discussed.

1. INTRODUCTION

Experience with application experiment systems and other PV field installations to date has demonstrated that array field balance-of-system (BOS) and engineering costs must be substantially reduced before PV power systems can be cost effective for grid-connected applications. Based on actual cost data (1) for a representative application experiment (a 100-kW flat-panel, ground-mounted installation), the array field BOS costs were \$424/m² and engineering costs were \$560/m² of collector area. These costs are far too expensive for widespread commercial interest, regardless of the cost of PV modules.

To significantly reduce these costs, a program (2) which emphasizes optimized and integrated array field subsystems and the development of standardized, modular building blocks which either alone or in

multiples can produce power levels ranging from 20 to 500 kW was undertaken. Two contractors, Battelle-Columbus Laboratories and Hughes Aircraft Company, were independently tasked with carrying out the objectives of this program for medium-size, flat-panel systems.

This paper will summarize the array field designs developed during this work with particular emphasis on key features, performance requirements, and projected costs. It should be noted that complete engineering drawing packages including detailed construction specifications are available for these designs.

2. DESIGN APPROACH

2.1 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 realistic cost reduction activities are appropriate. Fortunately, several medium size systems are currently operational and others are in various stages of construction. For the purposes of this paper, the Lea County Electric Cooperative application experiment was selected as being typical of a medium-size, ground-mounted, flat-panel system. This project, located at Lovington, NM, has a nominal system size of 100 kW with a peak system ac output of 101.5 kW_p. The system includes 1503 m² of collector area and was installed for a total cost of \$25.86/W_p of which \$9.51/W_p is due to the cost of PV modules. A detailed breakdown of all the system costs for this project will not be covered here. However, specific items have been examined for potential cost reduction activities. Table 1 lists these items along with proposed activities which were identified based on detailed examination of the major cost drivers for each subsystem.

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TABLE 1. MAJOR ARRAY FIELD ITEMS
REQUIRING COST REDUCTION

Item	Lea County System Cost	Cost Reduction Activity
Array Field Engineering Design	\$2.58/W _p	Develop standardized array field designs and building block hardware; minimize site specific design work
Structural Support Subsystem	\$114/m ²	Use low-cost foundations; develop integrated panel/structure hardware; use simplified mechanical attachment; maximize factory panel assembly
Site Preparation	\$137/m ²	Select sites with favorable conditions (minimal clearing and excavation work); relax leveling requirements
Field Wiring	\$173/m ²	Minimize subarray J-box installation and instrumentation; use quick-disconnect connectors; develop integrated field wiring designs

A key element of these cost reduction activities is the development of standardized array field designs and component hardware. Estimates of the site specific costs for the Department of Energy PV application experiments range from 50 to 60 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 PV installations.

Likewise, the cost reduction activities identified for the array field BOS subsystems have been incorporated in the designs developed by both Hughes and Battelle. These activities offer significant cost reduction especially from the viewpoint of a PV system as a commercial generating facility rather than a first-of-a-kind experimental project.

2.2 Requirements

To assure compatibility with other subsystem development activities, the following design requirements for the array field were specified.

- Field operating voltage of approximately 400 Vdc
- Compliant with applicable codes and safety requirements
- Suitable for installation at an Albuquerque site
- Module efficiency (for comparison purposes) of 10 percent at 80 mW/cm², AM 1.5, and NOCT

In addition, a program requirement was established whereby the design should be suitable for near-term use and that it should significantly reduce the costs of array field installations within the 1982-83 time period. This required that the design be implemented using materials and fabrication procedures presently available or readily developed. Similarly, to avoid the very expensive site preparation costs associated with many of the PV system application experiments, the array field design was constrained to be usable only in favorable sites. This requirement alleviated the need for the design to be universally applicable to all locations including such unfavorable sites as those with severe drainage problems or with surface bed rock.

It should be noted that the array field design activity did not include power conditioning equipment or any ac cabling downstream of this equipment. However, the designs have included interface requirements which are compatible with the current status in power conditioning hardware development.

In the next two sections, the array field designs developed by Battelle and Hughes will be presented in detail. The Battelle design was developed with subcontractor assistance from ARCO Solar, Inc.; Mission Research, Inc.; Motorola, Inc.; and Kellam and Associates, Inc. Similarly, Hughes was assisted by Solar Power Corporation and Frederick Costello, Inc.

3. BATTELLE BUILDING BLOCK DESIGN

The characteristics of the building block design developed by Battelle for use in low cost modular array fields are the following:

- PV Module - 0.6 x 1.2 m (2 x 4 ft);
5 Vdc output
- Parallel cell strings
- Bypass diode
- Foundation - Steel hat-section stakes
- Wolmanized 0.1 x 0.1 m
(4 x 4 in) beams
- Structure - Lightweight steel angle
and tubing
- Two-module panel,
1.2 x 1.2 m (4 x 4 ft)
- Intermodule Wiring - Crimp-spliced pigtailed
with insulating pad

- Field Wiring - Direct burial cables
- Building Block Size
 - 10 kW peak output @ NOC and 10% efficient modules
 - 400 Vdc @ NOC
 - Two modules in parallel, 82 pairs in series
 - Two rows of structure
 - 50 m (165 ft) east-west by 5.5 m (18 ft) north-south with aisles

Details of the design are described in a detailed engineering drawing package and construction specifications which have been prepared for use in installing array fields of the developed design (3).

3.1 Structural Subsystem

The design for the low cost structure and foundation which was developed is illustrated in Fig. 1.

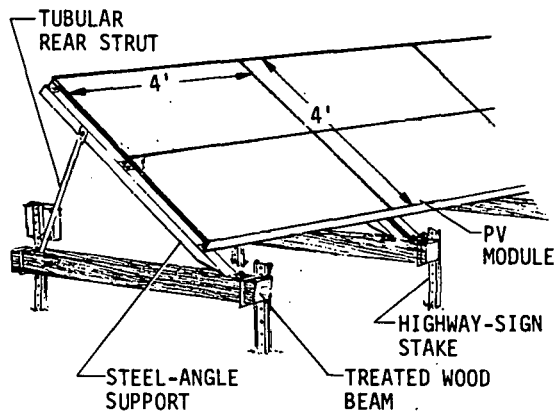


Fig. 1. Illustration of Building Block Structure and Foundation Design

Structurally, the basic unit of the array is a 1.2 x 1.2 m (4 x 4 ft) panel composed of two PV modules. The front steel-angle support is galvanized, as is the rear tubular strut which is simply formed from electrical conduit. The foundation stakes are galvanized hat-section steel stakes which are driven 1.1 m (3.5 ft) into the ground. U-bolts attach the stakes to the 0.1 x 0.1 m (4 x 4 in) wood transfer beams which have been treated for greater than 20-year lifetime. The wood beams permit simple fastening of the structural members using lag screws and provide flexibility in alignment during installation.

The principal attribute of the structure and foundation design is its very low cost for the components and their installation. Other advantages of the design are that:

- It is fabricated using simple parts that are immediately available without development

- It accommodates sites with uneven terrain and thereby allows for minimum site preparation
- The continuous metal structure reduces grounding costs
- All components can be handled by one person
- It is easily accessible for cleaning/maintenance from ground level
- It is simply automated with minimum investment.

3.2 Electrical Subsystem

As listed above, each pair of modules in a panel is wired in parallel, and there are 82 pairs in series in a building block.

As shown in Fig. 2, module wiring is accomplished using a crimp splice connection with an insulating cover pad applied. This connection method is appreciably lower in cost than other connection techniques considered.

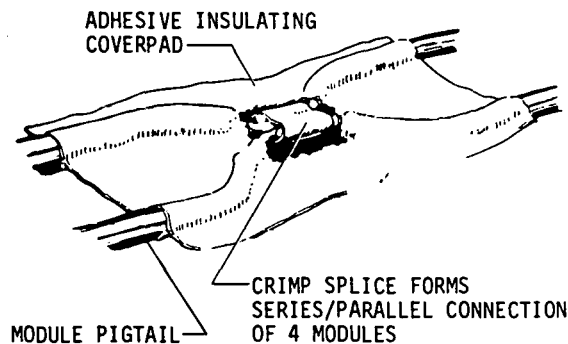


Fig. 2. Illustration of Module Interconnection Method

The building block operating at 400 Vdc corresponds to a branch circuit in this design, and there is one junction box per building block. Direct burial cable is used for the field wiring. Starting with the module, the electrical design of the building block was developed to provide a minimum lifecycle energy cost including considerations of minimum operation and maintenance requirements. The module is to contain parallel strings of cells, typically six parallel strings, each with eleven cells in series, and a bypass diode. This, combined with the pairs of parallel modules as noted above, minimizes the effect of normal rates of cell failure and allows for 20-year operation with an estimated degradation of power output of only 15 percent due to normal cell failures without replacing any modules during that period. For grounding, the continuous metal support structure is attached to a bare copper wire counterpoise network, which provides a uniform site ground. The primary attributes of the electrical design which has been developed for the building block are:

- Low component and installation cost
- Tolerance for the effect of cell failures on array power
- Low maintenance costs
- Use of structural components to minimize grounding costs
- In-field provision for isolation and testing of individual branch circuits.

3.3 Array Field Design

Detailed site layout drawings for construction have been prepared for 20-, 100-, and 500-kW-peak array fields, as examples of use of the building block design. These are included in the drawing package in Reference 3.

The 100-kW-peak field, for illustration, is composed of 10 building blocks, and thus has 20 rows of collectors. The overall area occupied is approximately 56 x 59 m (185 x 195 ft) including appropriate distances from the array to a surrounding security fence.

3.4 Cost Projections

The array field balance-of-system costs estimated for the developed building block design are shown in Table 2. These projections are based on quotations and estimates obtained from several general and electrical contractors and component suppliers using the final drawing package and construction specifications which were prepared. The basis provided for the estimates was a business volume corresponding to installing

TABLE 2. ARRAY FIELD BOS PRICE ESTIMATES FOR THE BATTELLE - DEVELOPED BUILDING BLOCK DESIGN

Item	1980 \$/m ²	
		Totals
Site Preparation		8.07
Survey, site layout	0.82	
Clearing, grading	2.31	
Vegetation Control	0.63	
Fencing	4.31	
Structural Subsystems		27.82
Structures	4.77	
Foundation	17.97	
Panel assembly and installation	3.85	
Shipping	1.23	
Electrical Subsystems		16.04
Grounding, lightning protection	4.83	
Junction boxes	4.08	
Panel wiring	4.38	
Field wiring	2.75	
		<u>51.93</u>

1 MW/yr of array fields of a typical size of 100 kW. Quotations were obtained as prices (including profit) in September 1981, and are converted in Table 2 to 1980 dollars (using a deflator of 0.917) for comparison with the value given in Table 1. It should be noted that the values in Table 2 are in dollars per square meter of PV module area.

The total array field BOS price of \$52/m² corresponds to approximately \$0.52/watt-peak, at rating conditions of 100 mW/cm², air mass 1.5, cell at NOCT, and 10% module conversion efficiency.

4. HUGHES BUILDING BLOCK DESIGN

The modular array field building block developed by Hughes is a \pm 200 Vdc bipolar unit with a nominal output power rating of 10 kW. The building block, which is a branch circuit, consists of two 200 Vdc monopolar subarrays positioned in an east-west oriented row. Each subarray structure accommodates two parallel circuits of 40 series-connected 5 Vdc PV modules. The building block characteristics are as follows:

- PV Module - 0.6 x 1.2 m (2 x 4 ft);
5 Vdc output
- Parallel cell strings
- Integral bypass diode
- Foundation - Earth covered steel footing in front; concrete curb in back
- Support spacing at 1.2-m (4 ft) intervals
- Structure - Lightweight steel angle
- Four-module panel, 1.2 x 2.4 m (4 x 8 ft)
- Intermodule Wiring - Folded daisy chain with AMP connectors
- Field Wiring - Direct burial cables
- Power collection center
- Ground fault detection
- Building Block Size - 10 kW peak output @ NUC and 10% efficient modules
- \pm 200 Vdc bipolar configuration
- One row of structure
- 53.9 m (177 ft) east-west by 2.4 m (8 ft) north-south

Specific details of the design are described in an engineering drawing package and construction specifications document (4).

4.1 Structural Subsystem

Each subarray structure, illustrated in Fig. 3, consists of 40 panel assemblies that attach directly to the foundation. A panel includes four 0.6 x 1.2 m (2 x 4 ft) modules mounted to steel channel side rails

that permit the modules to act as part of the panel structure. The panel side rails are attached, at the appropriate tilt angle, to steel channel stanchions secured in a front and rear row hybrid foundation at 1.2 m (4 ft) intervals. The front row foundation is a buried metal foot structure that is positioned in a trench and earth back-filled. This metal structure acts as a buried ground counterpoise and is an integral part of the grounding net. The rear row foundation is a concrete curb designed to withstand the primary wind lifting forces. All steel members are hot-dip galvanized to provide the required corrosion resistance.

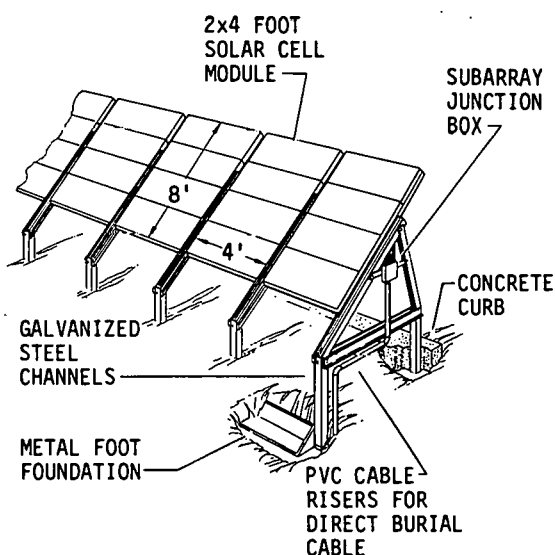


Fig. 3. Illustration of Subarray Structure and Hybrid Foundation Design

4.2 Electrical Subsystem

The electrical configuration of the building block unit is shown in Fig. 4. It consists of two 200 Vdc monopolar subarrays positioned in an east-west oriented row.

A + 200 Vdc bipolar system was selected for this design in lieu of a higher voltage monopolar system to permit the use of lower cost power components such as switch gear, MOV's, and blocking diodes. In addition, this configuration provides for convenient power distribution, enhanced safety, and sectionalization features. Various electrical subsystem concepts were evaluated during the study including circuit configurations using 5 and 15 Vdc modules. The results of circuit performance analyses showed that the use of 5 V modules reduced lifetime power loss through the utilization of additional parallel circuits protected by bypass diodes.

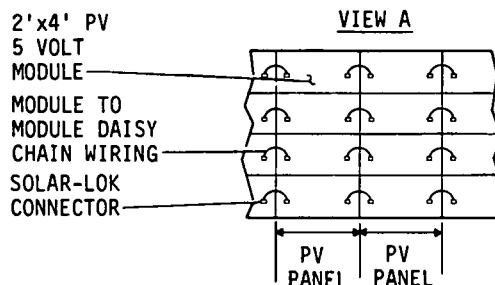
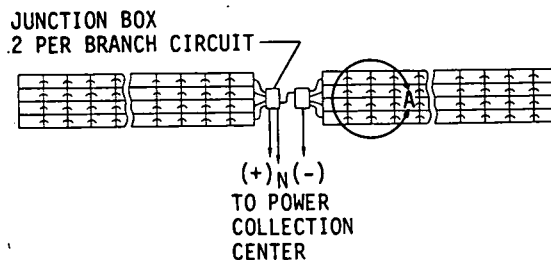


Fig. 4. Wiring Schematic for Array Field Building Block

The electrical design includes the wiring of PV modules in parallel horizontal rows. This geometrical orientation reduces energy loss due to row-to-row shading and variations in diffuse radiation along the slant height of the panels. A folded version of a daisy chain module-to-module wiring concept was selected whereby the circuits run in horizontal rows and fold back on themselves such that all input-output leads terminate in a common junction box at one end of the subarray structure. This approach utilizes a quick-disconnect cable assembly manufactured by AMP, Inc., and reduces installation cost as well as simplifies module diagnostics and replacement.

Power from each building block is routed from a subarray junction box to a power collection center (PCC) via direct burial cable. The PCC contains a standard circuit breaker switch and bus panel, fault detection sensing, and a power control module (PCM) for every two building blocks. Likewise, the PCM contains MOV's, blocking diodes, snubbers, and crowbar. The array field is thus sectionalized from a control standpoint in 20 kW increments.

4.3 Array Field Design

Detailed site layout construction drawings have been prepared (4) for 20-, 100-, and 500-kW-peak array fields as examples of using the building block design. The implementation of a nominal 100-kW array field using 10 building blocks is illustrated in Fig. 5.

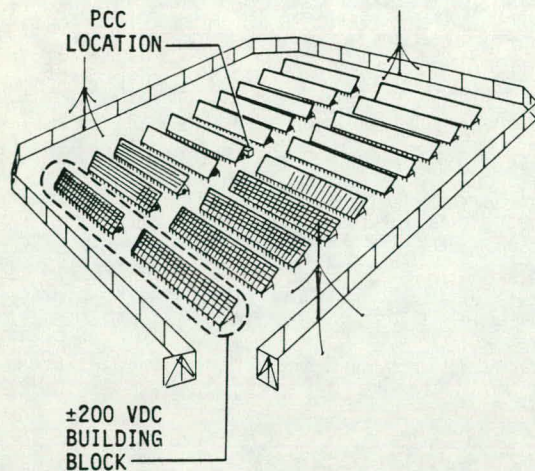


Fig. 5. 100 kW Array Field Layout

The fenced array field is approximately 66 x 74 m (217 x 242 ft) in size. As noted, the PCC is located in the center of the field. Although lightning rods are shown in the array field schematic, their use is recommended only in high isokeraunic areas.

4.4 Cost Projections

The array field BOS cost projections for this design, assuming an array field size of 100 kW, are shown in Table 3. These costs are estimated selling prices, excluding PV module costs, expressed in 1980 dollars and are based on a production volume of 10 MW/yr.

TABLE 3. ARRAY FIELD BOS PRICE ESTIMATES FOR THE HUGHES - DEVELOPED BUILDING BLOCK DESIGN

	1980 \$/m ²	
	Item	Totals
Site Preparation		9.46
Survey, cleaning, leveling	1.70	
Ground cover	2.04	
Fencing	5.72	
Structural Subsystems		34.70
Structures	10.60	
Foundation	16.56	
Panel assembly	1.00	
Transportation, crating loading & staging	6.54	
Electrical Subsystems		18.76
Field wiring and J-boxes	10.42	
Power collection center	4.84	
Lightning rods	.74	
Grounding net	2.76	
		62.92

5. CONCLUSIONS

Array field designs, optimized for lowest lifecycle energy cost, have been developed for PV system sizes ranging from 20 to 500 kW_p. These designs, developed through two separate studies, incorporate optimized and integrated array field subsystems and a standardized, modular building block which either alone or in multiples can generate the desired system power output. These designs are applicable for near-term (1982-1983) implementation and reduce the array field BOS costs to a fraction of those previously experienced. The designs also incorporate improved reliability relative to comparable existing installations and minimize maintenance requirements and costs. Based on estimated array field BOS costs (1980\$), 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. Similarly, the standardized designs and components should significantly reduce project engineering costs. Complete engineering drawing packages, including detailed construction specifications, are available for each design.

As a final note, prototype array fields, incorporating three modular building blocks each of the Hughes and Battelle designs, will be installed in the Sandia Photovoltaic Test Facility in Albuquerque during October 1982.

6. REFERENCES

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