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CONTRACTOR REPORT

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UC—63-a

Design of a Photovoltaic Central Power Station

Martin Marietta Corporation
Denver, CO

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185
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Design of a Photovoltaic Central Power Station

Martin Marietta Corporation
Denver Aerospace
Solar Energy Systems
PO Box 179
Denver, CO

Under Sandia Contract No. 62-9142

Abstract

Photovoltaic central power station designs have been developed for both high-efficiency flat-panel arrays and two-axis tracking concentrator arrays. Both designs are based on a site adjacent to the Saguaro Power Station of Arizona Public Service. The plants are 100 MW each, made of 5 MW subfields. The site specific designs allow detailed cost estimate for site preparation, installation, and engineering. These designs are summarized and cost estimates analyzed. Provided also are recommendations for future work to reduce system cost for each plant design.

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This report presents design summaries and future work recommendations for both the flat-plate and concentrator photovoltaic central power stations. This study was undertaken by the Solar Energy Systems Product Area of Martin Marietta Denver Aerospace with Arizona Public Service and Stearns-Roger Services, Corp as subcontractors. The program involved the development of two 100 MWe photovoltaic central power stations designs. Each design was done using good engineering design practices. Than the design was applied to a site specific location (Arizona Public Service's Saguaro Plant) to show its applicability for utility use.

ACKNOWLEDGMENTS

The personnel who participated and contributed in this study were:

Sandia Laboratories

Dr. Gary Jones, Technical Monitor

Martin Marietta Denver Aerospace

Matt S. Imamura, PV Array and Systems Engineering

Dave Hughes, PV Array and Systems Engineering

Lee Marshall, PV Array and Systems Engineering

Dr. Pat Hardee, Instrumentation, Control and Display

Jerry Stephenson, Power Conditioning

Bruce Heller, Financial and Cost Analysis

Arizona Public Service

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Stearns-Roger Engineering Corporation

William B. Lang, Program Manager

L. J. Dubberly, Project Engineer

Don Parker, Civil and Mechanical Engineering

Jim Walton, Electrical Engineering

Jerry Harris, Electrical Engineering

Jack Brock, Cost Analysis

In addition, thanks are extended to John Oster of Burt, Hill, Kosar, Rittleman Associates for array installation scenarios, and Joe King of UTC, Power Systems Division, for advanced inverter capabilities.

CONTENTS

Figures

Tables

Tables (Cont'd)

I. INTRODUCTION

The photovoltaic central station application has been addressed by a variety of system designers, utility planners, and economic analysts.[1,2] The result of these efforts has been the elucidation of general system-level requirements, utility value analyses, and general plant economics based on future technology. The purpose of the effort described in this report was to; build on these past results, refine the requirements to specific design criteria, produce detailed designs for both flat-plate and concentrator-array photovoltaic central power stations (PV CPS) at an actual utility-owend site, estimate their performance and initial construction cost, and suggest approaches to the problem design areas that will require study before a decision can be made to build an actual plant.

Martin Marietta in conjunction with Arizona Public Service and Stearns Roger as subcontractors have completed an initial task to develop a preliminary design of a Photovoltaic (PV) Central Power Station (CPS) at a utility power plant site. This contractual effort was originated and administered as part of the Department of Energy (DOE) Photovoltaic Systems Definition Project conducted by Sandia National Laboratories. The basic tasks in this study effort were as follows:

Design of Flat Plate PV CPS (SAND 82-7147)
Design of Concentrator PV CPS (SAND 82-7148)
Recommendations for Future Work/Final Report (SAND 82-7149)

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1 Bechtel National Inc., Research and Engineering Operation, Requirements, Definition, and Preliminary Design of a Photovoltaic Central Station Test Facility, Sandia National Laboratories Report, SAND 79-7012, April 1979.

2 Stolte, W.J., Bechtel Group Inc., Photovoltaic Subsystem Optimization and Design Trade off Study Final Report, Sandia National Laboratories Report, SAND 82-7013, March 1982.

Several studies of PV CPS have been sponsored by Sandia, DOE, Aerospace Corporation, and Electric Power Research Institute (EPRI).[3] These studies resulted in conceptual configurations with emphasis on general system design and economic issues. The purpose of this project was to make maximum use of previous study results to produce site specific designs for two CPS's, one utilizing a flat plate PV array and the other a concentrator PV array, incorporating technologies that are anticipated to be commercially available in 1985-1986. It is intended that this project develop PV CPS design data to assist in future system and subsystem development. Although this study is site specific (APS Saguaro), the results may be useful to any CPS applications in general.

Martin Marietta had the overall responsibility for the CPS design and PV power system. Stearns-Roger was responsible for architectural and engineering tasks (site layout, array foundations and module mounting structure, plant and facility layout, and ac electrical system configuration). Arizona Public Service actively participated in all study tasks, especially as related to utility interface requirements, operations and interactions.

A baseline configuration of the CPS, shown in Figure 1-1, has been assumed. It is comprised of the Photovoltaic Power System (PVPS), the ac Electrical system (acES), instrumentation, control and display (ICADS), and plant facilities and services (PFAS). The configuration is a 100-MW plant subdivided into modular blocks of 5 MW each. No dedicated storage was considered. Each of the 5 MW CPS modules contain one 5.0 MW array subfield and one 5 MW inverter. The inverter dc input voltage is a nominal 2000 Vdc. The inverter output of 480 Vac (3 phase) interfaces with an intermediate HV line via a step-up transformer. The output of this transformer is then coupled to the utility HV transmission network.

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3 Ibid. Bechtel, Stolte

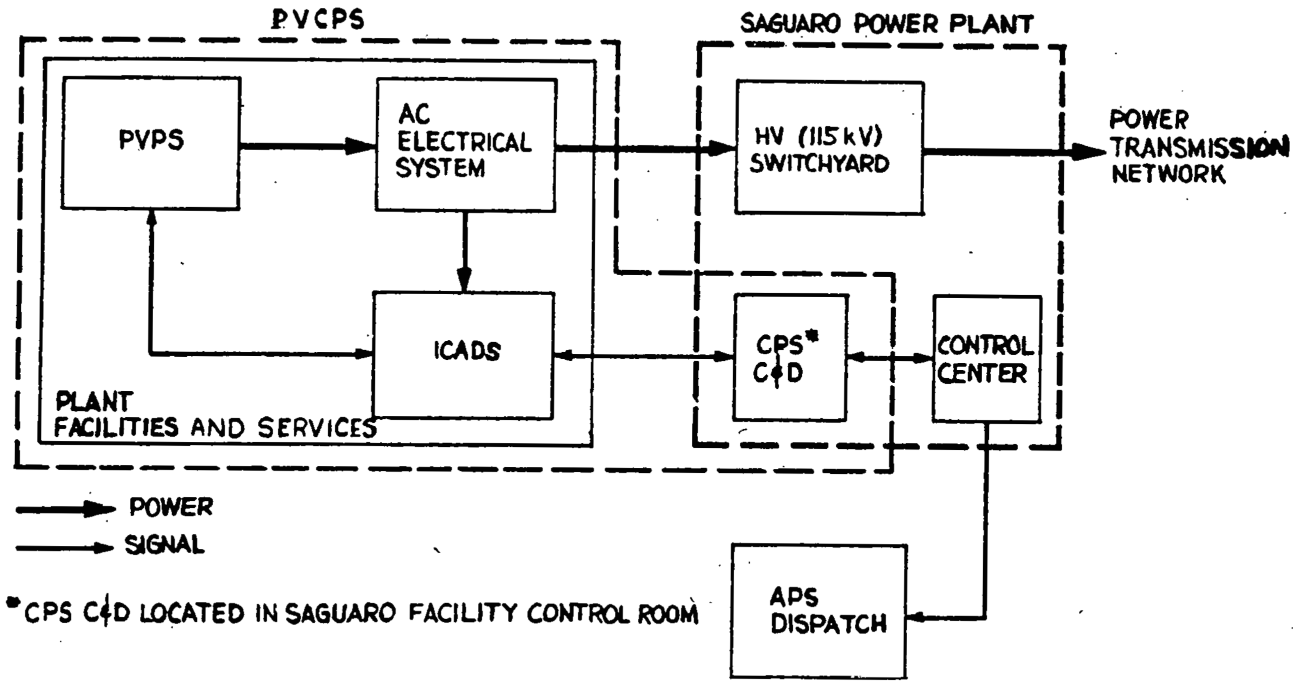

Figure I-1 Simplified Block Diagram of the 100 ME_e PV CPS

A set of guidelines were established during the initial kickoff meeting.

These are:

1) Peak CPS power rating: 100 MWe at the switchyard interface;
2) PV array dc voltage output: ± 1000 Vdc nominal;
3) PV array/inverter modular size: 5 MWe;
4) Use of existing utility practices as much as possible. These include:
   Technical standards
   Safety standards
   Security practices
   Building and construction codes
   Power control strategies
   Operation and maintenance procedures;

5) Use of technology hardware available forseen in 1985 to 1986 time frame. That is, hardware that are anticipated to have achieved commercial readiness by that time;
6) Use 8' x 20' flat plate arrays consisting of 4' x 4' modules for flatplates and make maximum use of Bechtel's subsystem tradeoff study results.[4]
7) Use Martin Marietta's second generation for concentrating arrays.

Two of the most important technical guidelines in the CPS configuration are the power plant capacity rating and the modular size of the array subfield. The minimum plant capacity of 100 MWe was recommended by APS for the following reasons:

1) A CPS rated at 100 MWe ac output would represent approximately 2.2% of APS's peak generating capacity in 1986 and 2% in 1990.
2. APS feels that 2% or more of the APS total output power capacity represents a significant amount of power which can "felt" on the high voltage transmission network.

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[4] Bechtel Group, Inc., "Photovoltaic Subsystem Optimization and Design Tradeoff study," SAND 81-7013, March 1981.

Bechtel's study indicates that the subfield should be sized between 2 and 10 megawatts for a central power station application. Bechtel also recommended a high voltage, approximately 2000 volts, for the PCU input voltage, as the most cost effective approach. Their analysis used a subfield configuration where each source circuit is individually connected to the main dc power bus (or the inverter). After analysis and discussions with Arizona Public Service and Stearns-Roger Engineering personnel, it was decided that the approach taken by Bechtel could be further enhanced. Taking into account the necessary considerations for switchgear, circuit protection, instrumentation, control, and electrical insolation, the subfield configuration could easily be one where multiple source circuits in parallel are fed into the inverter. For this study we used a 5 MWe PV subfield and a bipolar ± 1000 vdc for the source voltage. This selection of a 5MWe modular subfield is a relevant issue in configuring a PV central power station. Analysis on this approach is presented in the Task II and III reports.

The results of these tasks are documented in two design reports, one using flatplate technology (SAND 82-7147) and one for concentrator technology (SAND 82-7148), which present indepth design analysis of all major plant subsystems, including specifications, drawings, performance simulation, and an initial plant construction cost estimates.

The efforts conducted under Task IV, reported in this document, are intended to outline the major design problems encountered during Tasks I, II, and III, and suggest solutions for future studies. Areas for future study are organized into cost, hardware, and technical categories, ranked by the design team according to their impact on plant feasibility.

A summary of the major design requirements appears as initial discussion in Section II and is followed by a comprehensive design summary of both the flatplate and concentrator PV CPS. The design summary includes tabular comparisons of important design data such as land area requirements, module performance, field layout data, mounting and tracking structure descriptions, branch circuit power and voltage values, field cabling descriptions, lightning and grounding subsystems, PCU characteristics, in-field control and instrumentation, and detailed descriptions of access and security subsystems. Design details are clearly referenced to the individual Task II and III reports. Appearing as footnotes within each subsection are references to design data taken from other studies.

II. DESIGN SUMMARY

A. INTRODUCTION

This section summarizes the major features and design requirements for a representative 100 MWe flat-plate and concentrator photovoltaic Central Power Station (CPS) designs. These designs are discussed in detail in SAND 82-7147 and SAND 82-7148 for the flat-plate and concentrator respectively.

A set of guidelines (ground rules) were established during the program kickoff meeting in conjunction with the technical monitor at Sandia National Laboratories, Alburquerque, before the initiation of the design. In summary these can be stated as follows:

1) Peak CPS power rating: 100 MWe at the switchyard interface
2) PV array dc voltage output: ± 1000 Vdc nominal
3) PV array inverter module size: 5 MWe
4) Use technology hardware forseen to be commercially available in the 1985-1986 time frame.
5) Use existing utility practices to the extent possible. These are to include as a minimum:
   a. technical standards
   b. safety standards
   c. security practices
   d. building and construction codes
   e. power control strategies
   f. operation and maintenance procedures

6) Make maximum use of Bechtel's "Subsystem Design Optimization and Trade-off Study "results (Reference 1).

Two of the most important technical guidelines in the Central Power Station configuration are the power plant capacity rating and the modular size of the array subfield. To present a site specific example of how the design concepts can be used, the Saguaro Power Plant in the Arizona Public Services net was chosen. This site was recommended by APS because for a 100 MWe photovoltaic central power Station because:

a. Power output would represent approximately 2.2% of APS's peak generating capacity in 1986 and 2% in 1990.

b. APS felt that 2% or more of the APS total output power capacity represented a significant amount of power which can be "felt" on the high voltage transmission network.

c. Saguaro site was selected due to the load profile seen on the grid at this location and the wealth of data which was available about the site.

In the Bechtel study referenced above, they specify a range for the subfields between 2 and 10 MWe. As stated earlier, it was the decision of the program to use to 5 MWe subfield size. Bechtel also mentions a 2000 volt dc modular array subfield. It was decided to retain the 2000 volts, but to achieve it using a ± 1000 volt main dc power scheme. This decision appears to have value in reducing some of the insulation specifications within various parts of the total system.

Under each reference design four integral elements within the PV Central Power Station were identified: PVPS - the photovoltaic power system; asES - the ac electrical system; ICADS - the instrumentation, control, and display system; and PFAS - plant facilities and services.

B. PV CENTRAL POWER STATION DESIGN REQUIREMENTS

Key design criteria and requirements that must be addressed in the design of a photovoltaic central power station are discussed below. Special attention was paid to issues relative to utility interface with the PV plant. The following sections discuss the guidelines used for formulating design requirements, the rationale for identifying key requirements, and the problem areas resulting from these key requirements.

1. Study Guidelines

A major thrust in defining study guidelines was to outline the minimum set of design requirements for the PV central power station design consistent with obtaining minimum initial plant cost. Thus, it is hoped the flat-plate (SAND 82-7147) and concentrator (SAND 82-7148) design documents define generic requirements, even in the site specific design areas, allowing maximum utilization of the documents. It should be noted that such documents are subject to continual updates as the design evolves to increase its usability. Key element of design formulation was to ensure that utility interface requirements were addressed in detail by the utility subcontractor. This objective was accomplished by close coordination with the utility subcontractor, APS, in defining the utility interface.

Another guideline was to use existing central-station design requirements to the extent possible. A general assumption was made that the plant was to be a commercial endeavor and not an experimental test facility.

C. FLATPLATE DESIGN SUMMARY

A 1.32M x 1.32M, 178.8 We (peak), glass-covered, aluminum-framed, module containing dendritic web cells was chosen for use in the flat plate array. This photovoltaic module utilizes poly-crystalline ribbon cells with an assumed power conversion efficiency of 0.142. Current dendritic web silicon sheet technology has produced laboratory cells with approximately 16% efficiency. It was assumed that the module design and performance requirements would meet or exceed Section II, Block V Specification published by JPL.

Characteristics of the Photovoltaic Flat Plate Module

Size: 1.32m x 1.32m

Construction: Extruded Al Frame, EVA Pottant, 0.32cm fully-tempered glass, 0.13mm craneglas, mylar backing

Cells: Dendritic web, silicon

NOCT: 44°C

Bypass diode: 1 per module

Aperture: 1.486 m^2

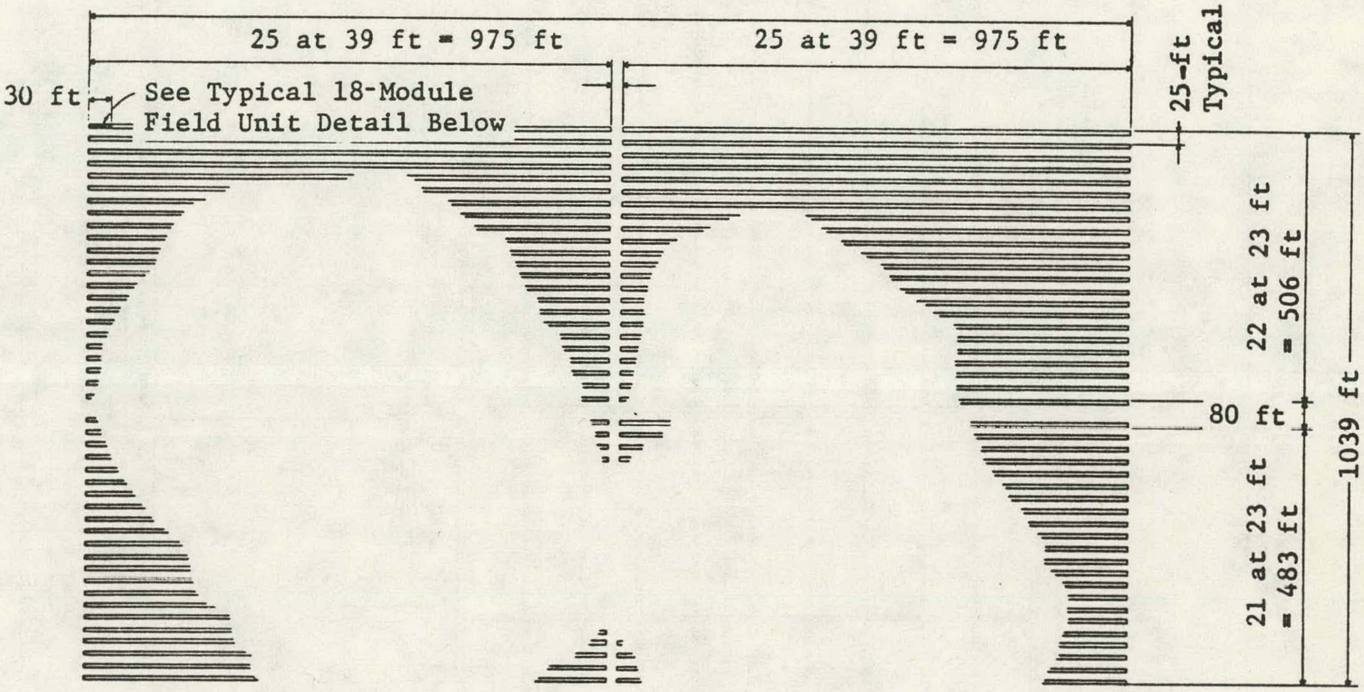
Performance

	Peak Conditions 1000 w/m^2, AM 1.5, 28°C Cell	Nominal Conditions 800 w/m^2 AM 1.5, NOCT
Cell Efficiency	0.142	0.133
Module Efficiency	0.122	0.113
Voc	24.5 Vdc	24.4 Vdc
Isc	9.52 A	7.61 A
Vmp	19.91 Vdc	19.81 Vdc
Imp	8.98 A	6.80 A
Pmp	178.8 We	134.7 We

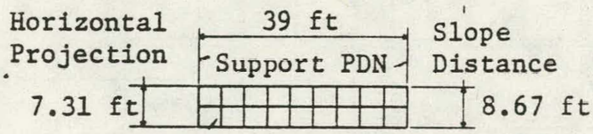
Using the PV module described above, the next step is to arrange these into a suitable panel to facilitate field installation. A panel shall be defined as the smallest field installable PV component here consisting of eighteen (18) modules. The panel will measure 2.64 meters x 11.9 meters, and will consist of two rows of nine modules factory assembled and pre-wired in series (Drawing 849PCPS1230).

To complete the entire 100 MWe field, 45,000 panels would be organized into twenty, 5MWe subfields each with an individual inverter (PCU). The PVPS array field layout depicting the arrangements of subfields and other plant facilities appear on Drawing 849PCPS1226. The total land requirements for the flat plate PV Central Power Station is 1.56 square miles. The array field area requires 1.35 square miles.

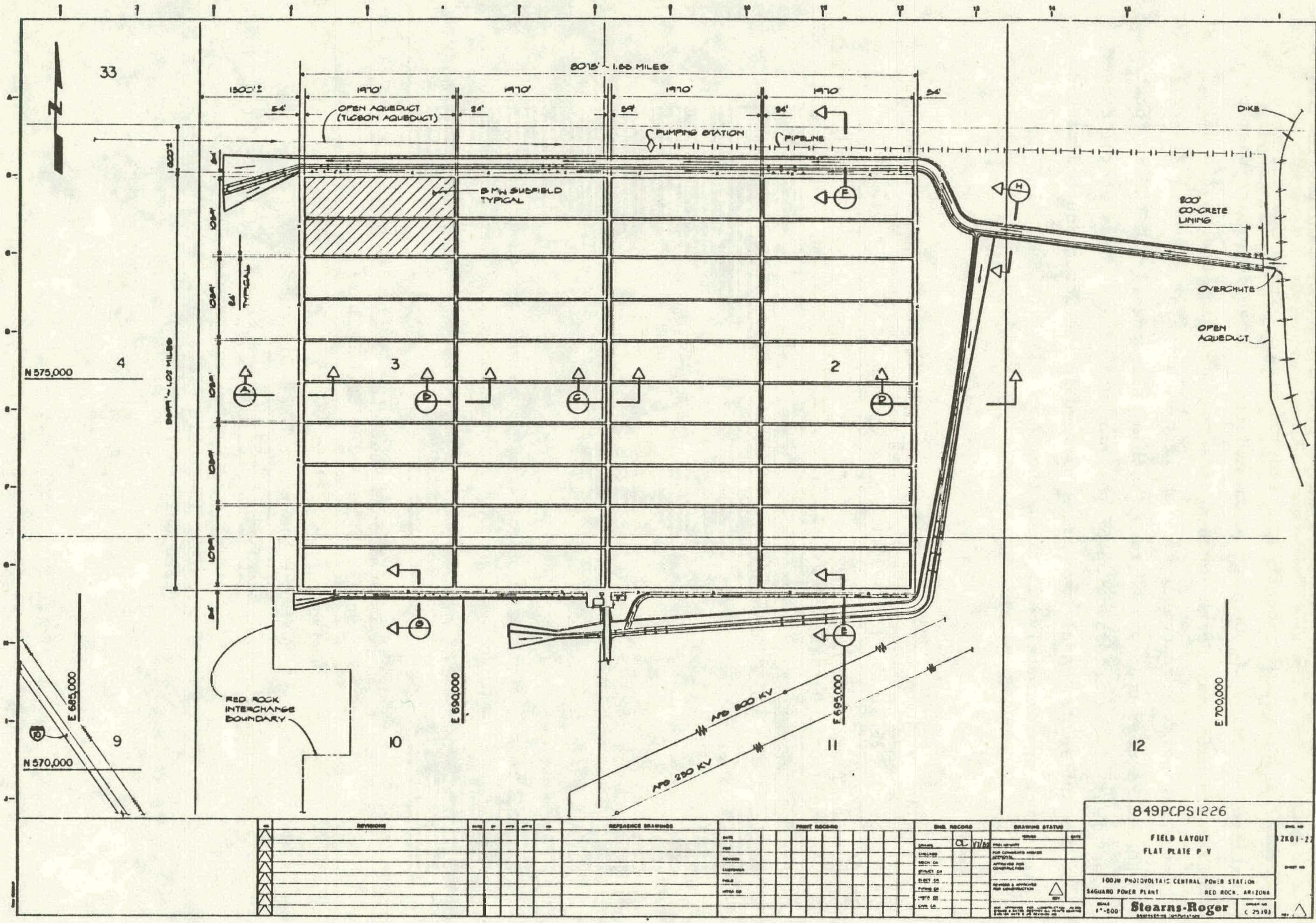
The choice of a 5 MWe subfield modular size was based upon the results of Bechtel's Subsystem Tradeoff/Optimization Study. The 5 MWe subfield utilized contains 40,500 flat plate modules arrange into East-West rows of 50 panels each with North-South access road dividing the row in half. The East-West array rows number 45 with 23 rows north of the main East-West subfield access road and 22 rows South of this road. The PCU is located just East of the intersection of the subfield access roads at the center of the subfield. Panel rows are separated in the North-South direction by 5.4 m, or approximately 2.5 times the panel slant height.



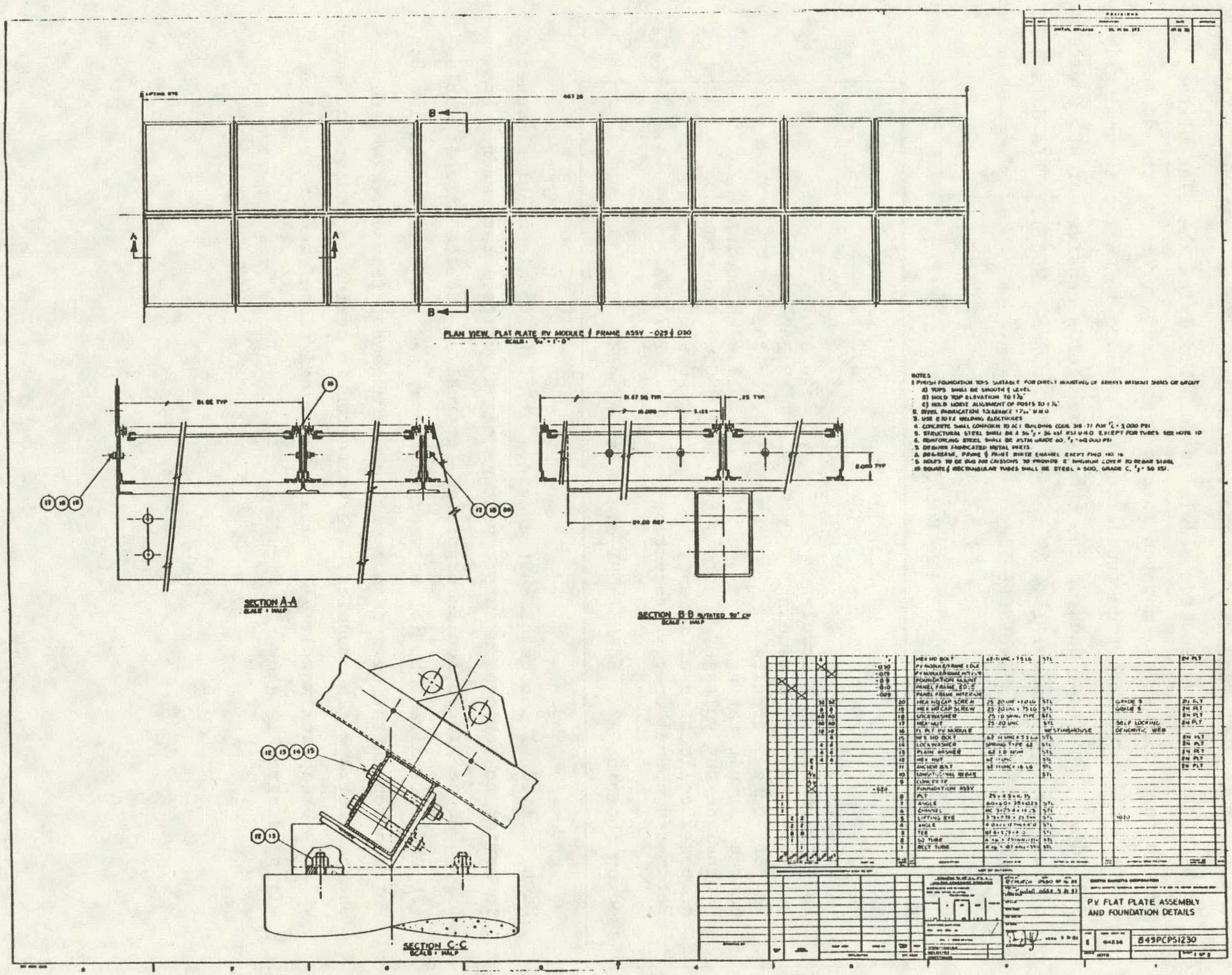
Typical 5-MW Subfield
Scale: 1 in. = 100 ft (20 Thus)



4 ft-4 in. x 4 ft-4 in. Modules Typ
Typical 18-Module Field Unit
(2250 Units per Subfield)



8015' ~ 1.55 MILES
1300'±
1970'
1970'
1970'
1970'
54'
OPEN AQUEDUCT
(TUCSON AQUEDUCT)
PUMPING STATION
PIPELINE
DIKE
5 MW SUBFIELD
TYPICAL
800'
CONCRETE
LINING
OVERCHUTE
OPEN
AQUEDUCT
N 575,000
N 570,000
E 685,000
E 690,000
E 695,000
E 700,000
RED ROCK
INTERCHANGE
BOUNDARY
APS 500 KV
APS 230 KV
33
4
3
2
9
10
11
12
849PCPS1226
FIELD LAYOUT
FLAT PLATE P.V
100MW PHOTOVOLTAIC CENTRAL POWER STATION
SAGUARO POWER PLANT
RED ROCK, ARIZONA
1"=800'
Stearns-Roger
C 25191


PLAN VIEW, FLAT PLATE PV MODULE & FRAME ASSY -029 & 030
SECTION A-A
SCALE: HALF
SECTION B-B ROTATED 90° CW
SCALE: HALF
SECTION C-C
SCALE: HALF
NOTES
P.V. FLAT PLATE ASSEMBLY
AND FOUNDATION DETAILS
849PCPS1230

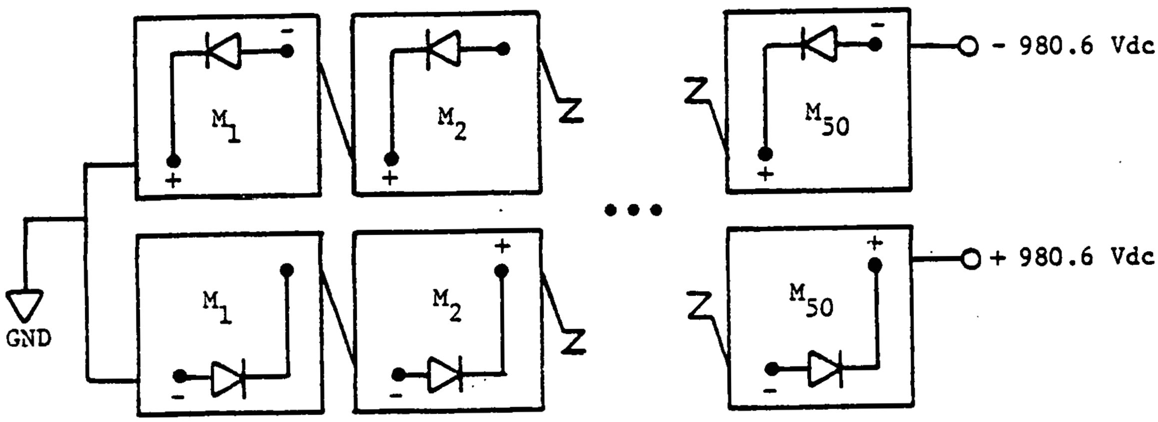
A bipolar (± 1000 Vdc) bus was chosen to allow a lower voltage isolation requirement thereby reducing module costs. Utilizing the flat plate module described above, mounted into a panel configuration, the dc bus voltage which results from connecting 100 modules in series is nominally ± 981 Vdc. Therefore, each of the twenty subfields consists of 405 source circuits with a nominal 13.4 KW rating (800 mw/cm^2, NOCT). This data is summarized below in Table II-1.

Table II-1 5 MWe Subfield Characteristics

Land (total)	20.2 ha
Land (array)	17.5 ha
No. 1.32 m x 1.32 m modules	40,500
No. 2.64 m x 11.9 m panels	2,250
No. of source circuits	405
Source circuit rating	13.4 kW nominal
Nominal dc bus voltage	± 980. 6 (to ground)
dc power collection efficiency	0.9806
Estimated annual energy production*	247 GWh

*Based on Phoenic, AZ. SOLMET-TMY data (see Appendix F)

Each individual source circuit consists of 50 flatplate modules connected in series to achieve an output voltage of 980 volts. Each module has bypass diode protection incorporated internally. Source circuit cables (#8 AWG) are direct burial between the array and the dc distribution box. For the concentrating system a similar arrangement is used. Two and one-half arrays (150 modules) are connected in series to achieve an output voltage of approximately 978 volts. A typical flatplate source circuit wiring diagram is shown in Figure II-3.



Key: M_n - 1.32 m X 1.32m Module n (1 ≤ n ≤ 50)

Bypass Diode (Within Module)

Figure II-3 Source Circuit Schematic

A total of 46,800 concrete piers are required for the 100 MWe flatplate photovoltaic field. Pier diameter is 18 inches; above grade height measures 2.5 feet with below grade depths varying to meet site conditions (At Saguaro the depths would range from 8.5 to 12.5 feet depending on field location). Structural reinforcement is provided within the foundation by five vertical reinforcing steel bars and circular ties set at 18 inch spacings. The 8 foot by 20 foot photovoltaic panel assemblies are installed with the aid of a forklift as shown in Figure II-4.

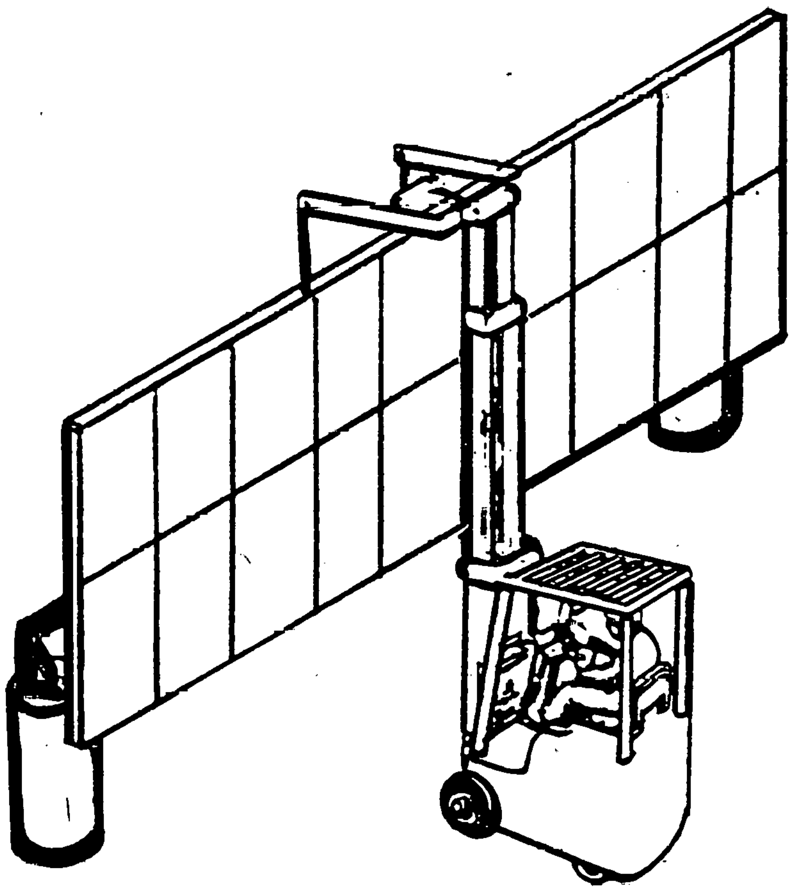


Figure II-4 Flat Plate Panel Installation

D. CONCENTRACTOR DESIGN SUMMARY

Utilizing Martin Marietta's second generation concentrator array, a 100 MWe central power station was developed. This specific concentrator was chosen due to the maturity of the design and the fact that approximately 500 kw of the earlier design has already been installed and there is good cost and performance data available from the systems. The array field consists of 22,000 arrays utilizing 1,320,000 modules. Each module is 0.43 meters by 1.47 meters in length. These are arranged into a 13.5 meter long by 3.5 meter wide array containing 60 modules. The sixty (60) modules are mounted on a support tube which is an integral part of a two-axis drive mechanism. These array assemblies (22,000 total for the 100 MWe field) are connected in series to form a source circuit generating 21.1 kw dc output at ± 977 Vdc (800 W/m^2 insolation, AM 1.5, NOCT - 71°C). In the same manner that the flatplate design was divided into modules, the concentrator design consists of twenty, five megawatt subfields. Each subfield contains 1100 arrays. Using five arrays to form a source circuit, there are 220 source circuits in each subfield which feed a dedicated 5 MVA power conditioning unit (inverter). In the same manner that was done for the flatplate, the 480 volt ac inverter output is fed into a step up transformer.

The concentrating module selected for the central power station is a fourteen lens/cell module, shown in Figure II-6. The module measures 1.46 meters x 0.42 meters and includes fourteen 20.73 cm square Fresnel lenses and fourteen specially designed 2.67 cm square passively cooled. Passive cooling of the concentrating cell occurs via convection (either natural or wind induced). Convection heating of adjacent cell assemblies is not a concern due to the spacing between heatsink assemblies. All the cells in the module are electrically connected in series with a single bypass diode. The module utilizes cells with an assumed power conversion efficiency of 0.193. Justification of the assumption for 1986 cell technology was provided by the existence of laboratory cells with currently measured efficiencies of slightly greater than 0.20. Table II-2 summarizes the basic module performance assumptions used for this study.

Table II-2 Photovoltaic Module Characteristics

Size 1.46 m x 0.42 m

Construction: Polymethacrylate Frensnel lens, injection molded ABS houring, die cast aluminum heat sink, alumina cell substrate

Cells: Single Crystal, Float zone silicon

Bypass Diode: 1 per module

Cell Cooling: Passive in ambient air

Aperture: 0.60 m^2

Concentration Ratio: 138 (Geometric); 100 (effective)

Lens Efficiency: 0.87 in an air Mass (AM) 1.5 spectrum over. 4 um to 1.1 um wavelengths

Performance

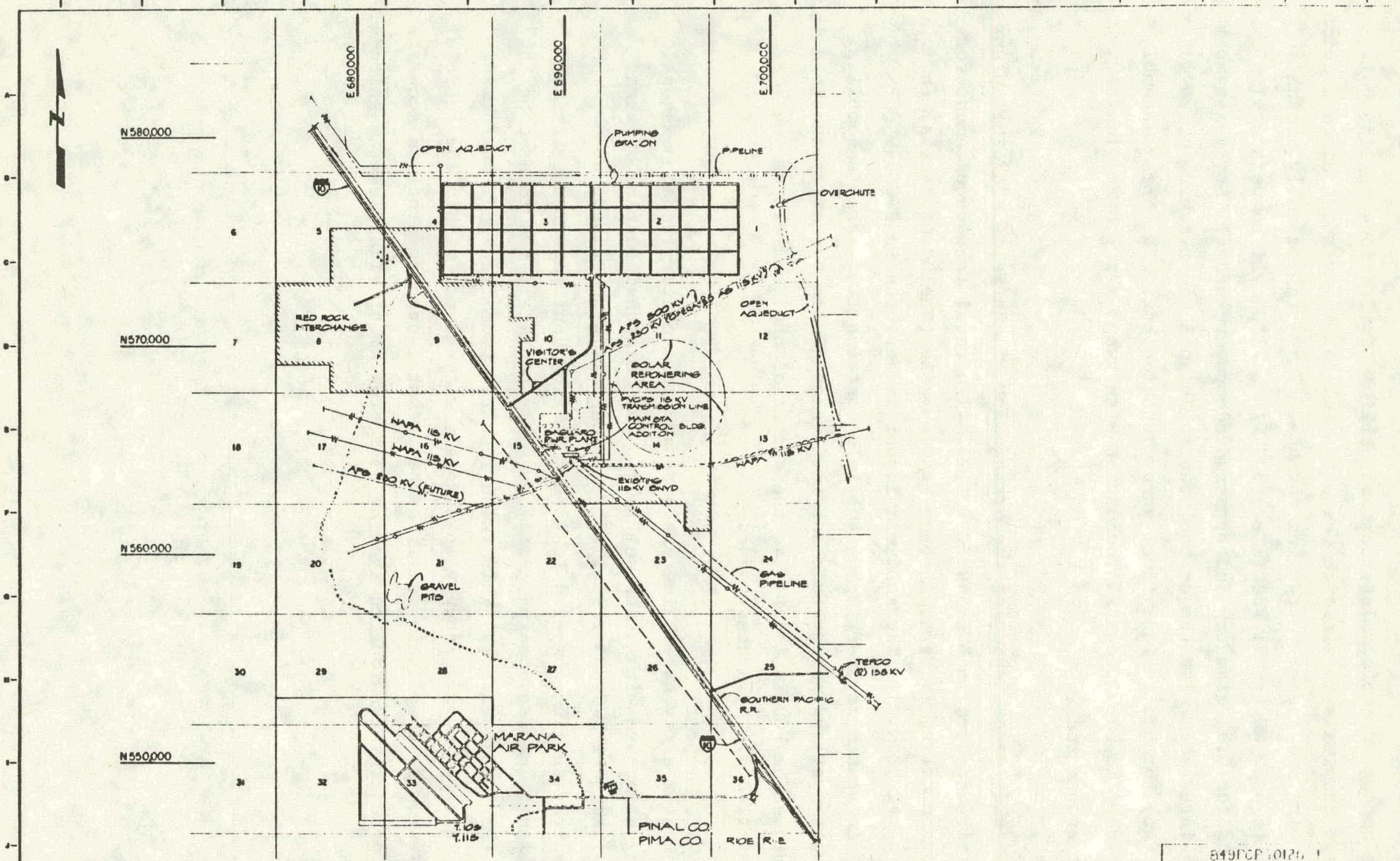
	1000 W/m^2, Direct Normal AM 1.5, 28°C Cell	800 W/m^2 Direct Normal AM 1.5, 71°C Cell
Cell Efficiency	0.193	0.160
Module Efficiency	0.177	0.147
Voc	9.95 Vdc	8.312 Vdc
Isc	14.59 A	11.67 A
Vmp	7.8 Vdc	6.52 Vdc
Imp	13.65 A	10.85 A
Pmp	106.45 W	71.3 W

As stated earlier in this section, sixty concentrator modules populate an individual mounting/tracking structure (array) assembly. The assembly is 13.5m long and 3.3 m wide with a central-pedestal mounted tracking drive assembly (see Figure II-6). Tracking control is implemented by an 8-bit microprocessor-based sun tracking unit (STU). Tracking accuracy is ± 5 arc-minutes (nominal).

All modules are serially interconnected on the array assembly via #10 AWG, single conductor cable. Interconnect cabling terminations utilize bolt-on lug type terminals to minimize the potential for inadvertent disconnection due to wind and assembly tracking motions. The array assembly nominal output is 4.22 kW at 391 Vdc (i.e., 800 W/M^2, 71°C cell temperature) allowing for 0.5% mismatch and bypass diode power losses. Array assembly wiring interfaces with the dc bus, control/signal and tracking/drive motor power (ac) through an individual array junction box. The array assembly is grounded at each pedestal foundation with two 3 m x 1.6 cm diameter copper ground rods.

Array field layout depicting the arrangement of subfields and other plant facilities appears in DWG 849 PCPS 1126. The total land requirement for the concentrating PV Central Power Station site (including access) is 592.3 ha (2.38 mi^2). The subfield layout is depicted in DWG 849 PCPS 1127. As stated earlier, 5 MWe subfield contains 1100 array assemblies. Main east-west and north-south subfield roads divide the array subfield in quarters. The PCU is located at the center of the subfield at the intersection of the access roads.

Concentrator array assemblies are arranged in a center-loaded hexagonal packing structure within the subfield. The hexagonal packing of array assemblies (see DWG 849 PCPS 1127) provides a minimum amount of intra-array shading compared to linear packing configuration, with an overall smaller land usage. Array assembly pedestals are located on 16.75 meter (55 feet) centers. This value resulted from trade-off performed using an array shading/energy loss model. It was not within the scope of this design to completely optimize the pedestal spacing since an accurate model of energy loss due to shading is a problem of significant magnitude.

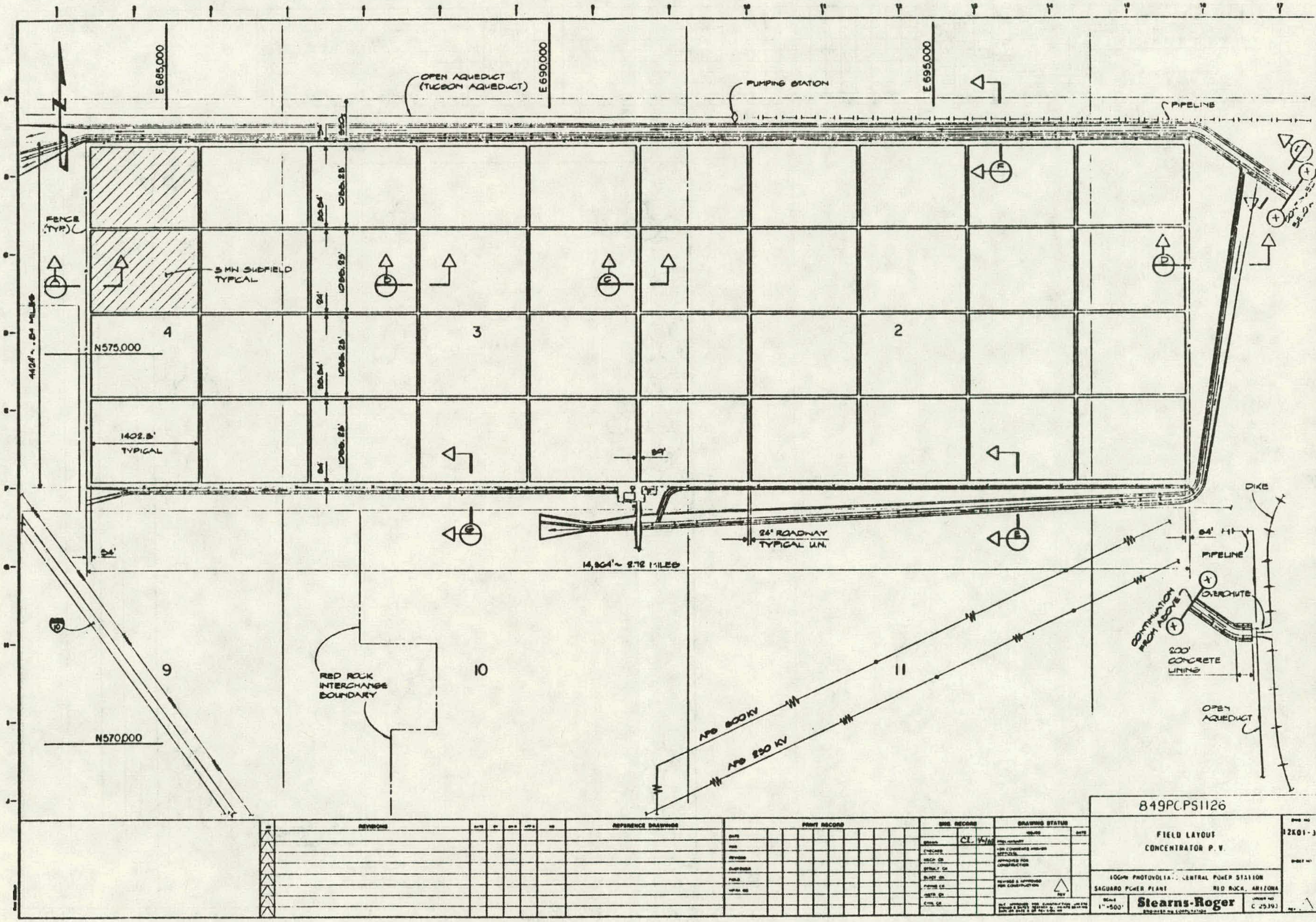


849FCP 50126 1

SITE PLAN
CONCENTRATOR P.V.

Stearns-Roger

20



E 685,000
E 690,000
E 695,000
OPEN AQUEDUCT
(TUCSON AQUEDUCT)
PUMPING STATION
PIPELINE
FENCE (TYP)
5 MW SUBFIELD TYPICAL
4
3
2
N575,000
N570,000
4424' ~ .84 MILES
1402.3' TYPICAL
1088.25'
24'
84'
24' ROADWAY TYPICAL U.N.
14,864' ~ 2.72 MILES
DIKE
PIPELINE
OVERCHUTE
CONTINUATION FROM ABOVE
200' CONCRETE LINING
OPEN AQUEDUCT
9
10
11
RED ROCK INTERCHANGE BOUNDARY
APS 500 KV
APS 230 KV
REVISIONS
REFERENCE DRAWINGS
PRINT RECORD
DRAWING STATUS
849PCPS1126
FIELD LAYOUT
CONCENTRATOR P.V.
100MW PHOTOVOLTAIC CENTRAL POWER STATION
SAGUARO POWER PLANT
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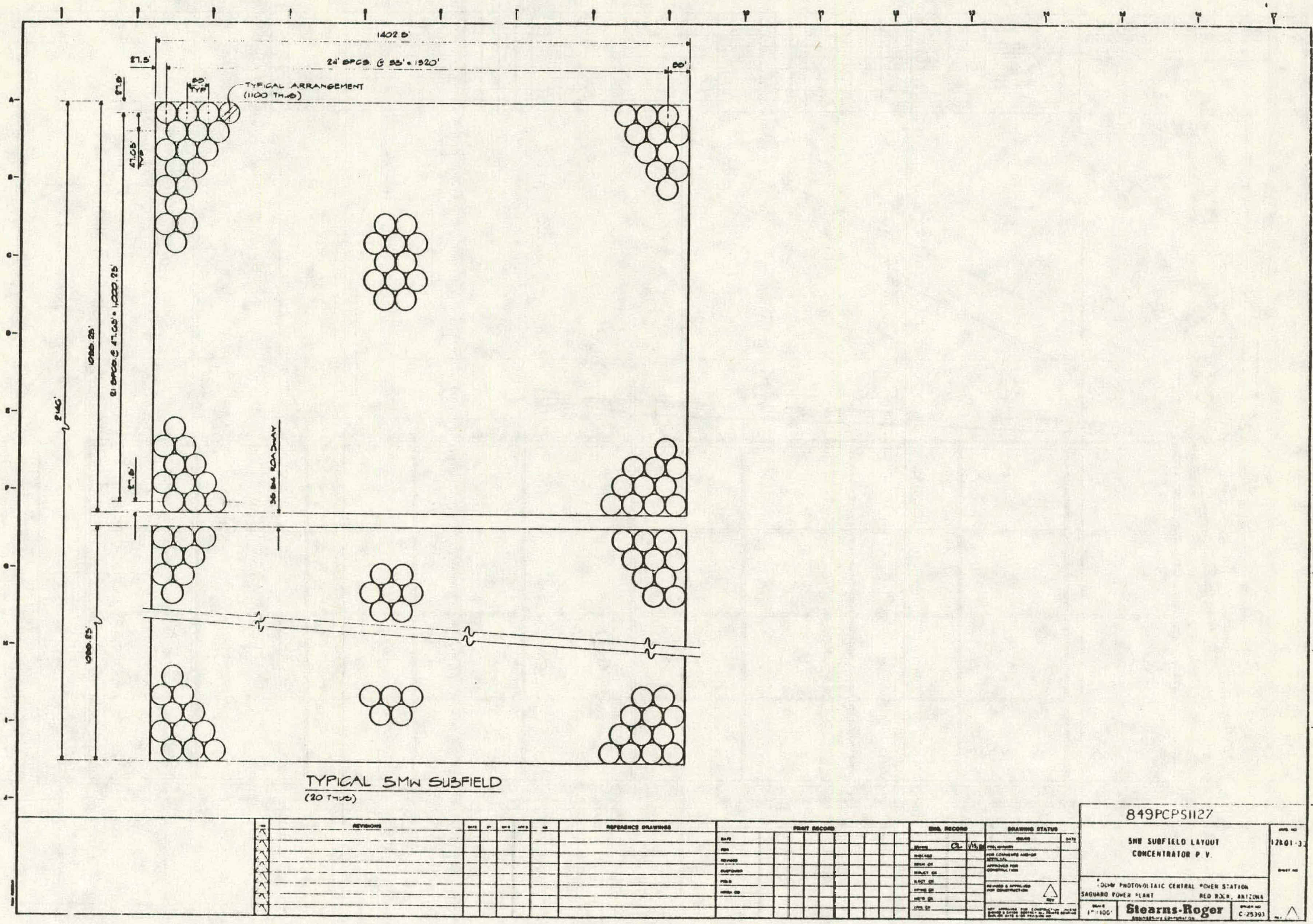

1402.5'
24' SPCS. @ 55' = 1320'
27.5'
55'
TYPICAL ARRANGEMENT (1100 THUS)
47.05' TYP
21 SPCS. @ 47.05' = 1,000.25'
1088.25'
2146'
30 Bd. ROADWAY
1088.25'
TYPICAL 5MW SUBFIELD
(20 THUS)
REVISIONS
REFERENCE DRAWINGS
PRINT RECORD
ENG. RECORD
DRAWING STATUS
849PCPS1127
5MW SUBFIELD LAYOUT
CONCENTRATOR P.V.
100MW PHOTOVOLTAIC CENTRAL POWER STATION
SAGUARO POWER PLANT
RED ROCK, ARIZONA
1" = 100'
Stearns-Roger
C-25393
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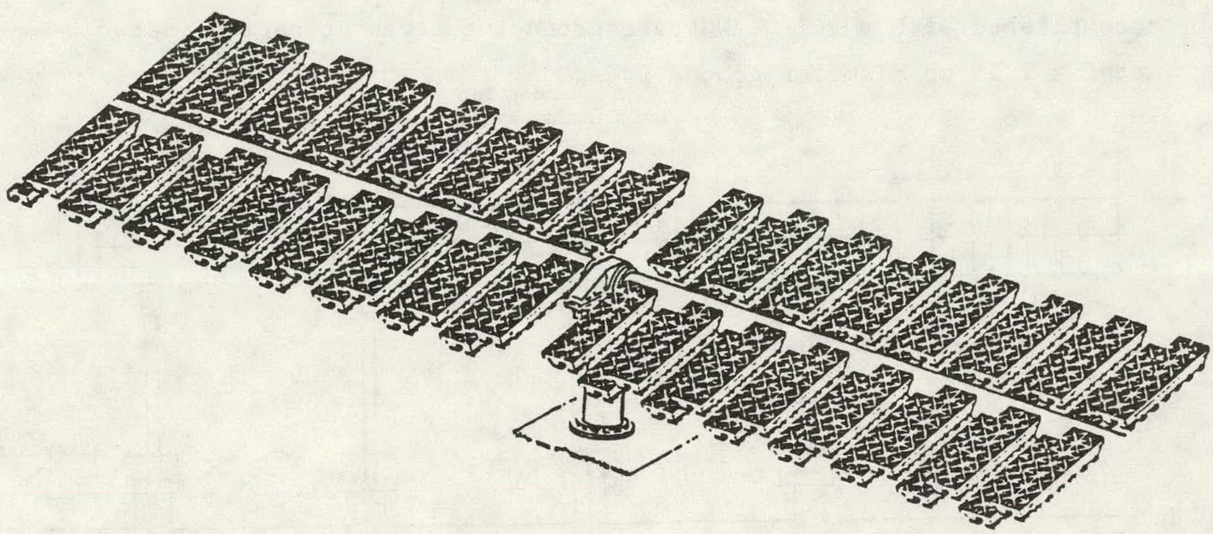

Figure II-6 Photovoltaic Concentrator Array Assembly

Utilizing the concentrating array/module described above, the design data for the 5 MWe subfield can be seen summarized on Table II-3.

Table II-3 5 MWe Subfield Characteristics

Land (total)	592.3 ha
Land (array)	549.6 ha
No. 1.46 m x 0.42 m modules	66,000
No. 13.5 m x 3.3 m array assemblies	1,100
No. of branch circuits	220
Branch circuit rating	21.1 kW nominal
Nominal dc bus voltage	± 977.5 (to ground)
dc power collection efficiency	0.9794
Annual energy production	14.2 Gwh

A source circuit wiring diagram is shown in Figure II-7. Source circuit cables (#8AWG) are direct buried between the array junction boxes and the dc distribution boxes. The center-top ground is physically located at the third array assembly junction box. Array assembly grounding is accomplished with a # 1/0 AWG bare grounding strap connected to two 3 meter x 1.59 an diameter ground rods.

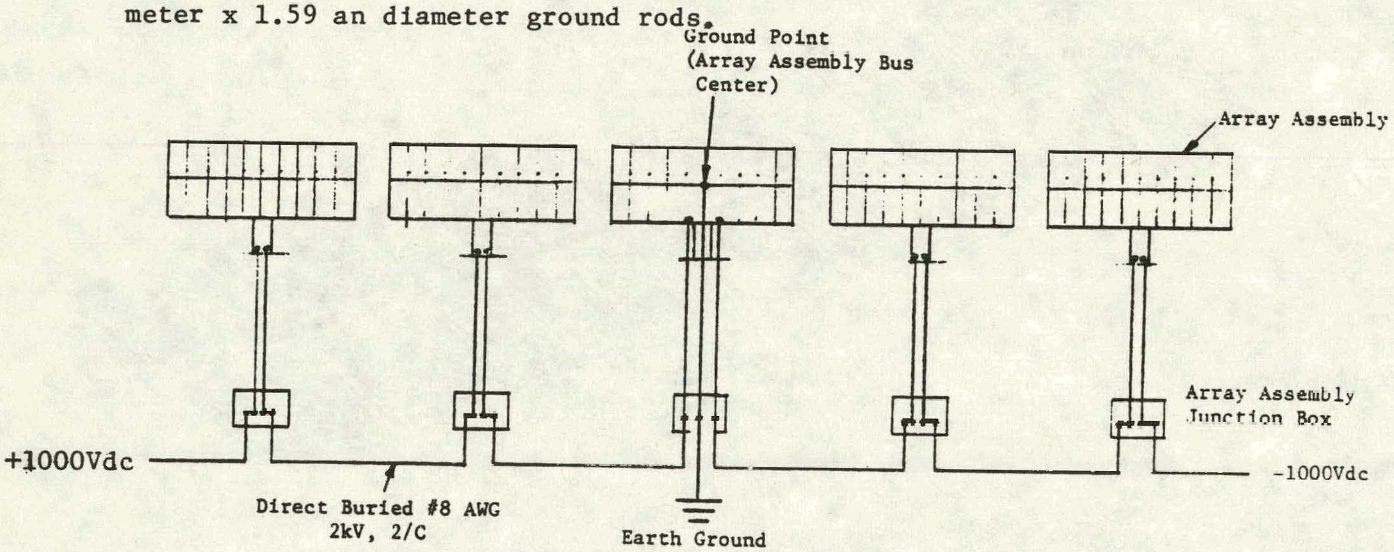

Figure II-7 Source Circuit Schematic

E. SUMMARY OF PHOTOVOLTAIC FIELD AND EQUIPMENT

A summary of the field configuration and equipment for the flatplate and concentrator PV designs discussed in sections 3.0 and 4.0 above is presented below.

Table II-4 Summary of Photovoltaic Field Design Data

Item	Description		Quantities		Performance Values	
	Flat Plate	Conc	Flat Plate	Conc	Flat Plate	Conc
Module	Dendritic Web Cell, Al frame	100X Float-Zone Si Cell, Point-Focus Fresnel lens	810,000	1,320,000	134.7W*	70.7W+
Panel (18 Modules)	11.9mx2.6m	—	45,000	—	2.4kW*	—
Array (60 Modules)	—	13.5mx3.3m	—	22,000	—	4.60kW+
Branch Circuit	100 Modules (Series-Connected)	300 Modules	8,100	4,400	13.4kWe*	23.0kWe+
Bypass Diode	One Per Module				—	—
dc Bus Voltage (to Ground)	Branch Circuit Voltage		—	—	±980.6V*	±977.5V+
dc Power-Collection Efficiency	Accounts for Losses in Blocking diode, Wiring and Losses due to Branch Circuit Mismatch		—	—	0.9806*	0.9794+
Subfield	405 Branch Circuits	220 Branch Circuits	20	20	5.32MWe ac	5.06MWe ac
Field	404 ha Land	592 ha Land	—	—	106.4MWe ac	101.2MWe ac

*800 W/m^2, 40^{o}C Cell Temperature (NOCT)

+800 W/m^2, 71^{o}C Cell Temperature

Table II-4 PVPS Equipment Summary

Item	Description		Plant	Quantity
	Flatplate	Concentrator	Flatplate	Concentrator
Module Assembly	1.32mx1.32m	1.47mx0.43m	810,000	1,320,000
Ground Rods	1.59cm dia.x3m		3,600	44,000
Intermodule Wiring	1/c, No. 8 AWG, 2kV	1/c, No. 10 AWG, 2kV	4,374,000 ft	3,160,600 ft
Concrete Piers	0.46mdia.x 3.4- to 4.6-m	0.46m dia.x4.9m	46,800	22,000
Tracking Assembly	--	Active Feedback, Sun-Sensing, Two-Axis Drive Mechanism	--	22,000
Array Junction box Lightning Arrestor	2.7kV GE Tranquel		880	880
dc Cabling (Branch Circuit)	2/c, No. 8 AWG, 2kV		3,800,000 ft	2,342,560 ft
dc Cabling (PCU) Feedere Circuit)	3/c, No. 4/0 AWG, 2kV		130,000 ft	316,360 ft
dc Distribution Box	Provides dc Cabling Taper No.8 to No.4/0		440	440

Table II-4 PVPS Equipment Summary (cont)

Item	Description		Plant Quantity	
	Flatplate	Concentrator	Flatplate	Concentrator
Signal Cabling	--	No. 19 AWG, 600V Armored --		1,452,000 ft
Inverter	5MVA	5MVA	20	20
PCU Aux Power Transformer	2kV/480V		20	20
Step-up Transformer	2kV/34.5kV		20	20

F. POWER CONDITIONING UNIT (PCU)

Both the flatplate and concentrating designs utilize twenty 5 MWe subfields. Each subfield uses a 5 MVA inverter, step-up transformer, auxiliary power transformer and associated switchgear. The PCU consists of skid-mounted inverter, transformers and switch gear. Inverter capabilities are assumed in places to represent what will be commercially available in the 1986 time frame.

The dc power from the photovoltaic bus will be converted to ac power with a solid state, static inverter. The inverter is rated at 5.0 megawatts continuous and will supply three phase power into a standard 60 Hz power grid. The inverter was sized to supply a 10% overload capability for 30 seconds.

A self-commutated inverter was selected over the line-commutated type. The cost advantages of self-commutated types are apparent when the installation costs are compared. The line-commutated inverters require larger rectifier transformers; their output filters are larger and much more expensive. The line commutated inverters also require more power factor correction hardware.

The voltage window (the ratio of the maximum dc input voltage divided by the minimum) should be 1.5:1 at a power level of 5 megawatts. This yields a 1600-2400 Vdc operating range

Key characteristics of the PCU for both PU designs can be summarized and shown as follows:

<u>INVERTER</u>

Description:	4.95 MW Solid-State, Static, Self-Commutated Inverter Using Pulse-Width-Modulated Switching

Efficiency:	96.5% at Nominal Full Rated Input, 94.0% at 1/4 Input
Input Voltage Window:	1.5:1 (1600 Vdc to 2400 Vdc) at 5 MW
Total Harmonic Distortion:	5% rms on the Output Current Waveform

G. AC ELECTRICAL SYSTEM (acES)

The ac electrical system provides the transmission and collection of subfield power outputs to the fields 34.5 kV/115kV switchyard, and 115 kV transmission to the utility grid. A system-level description of the PV central power station and the associated ac electrical system may be obtained by analyzing the plant one-line diagram (DWG 849 PCPS 2001-1).

TRANSFORMERS

i) 2000V-34.5kV Delta-Wye (Steps Up Inverter Output Voltage to Intermediate High Voltage)

ii) 2000V/480V Delta-Delta (Provides Auxiliary PCU Power Requirements and Utility Voltage Synchronization Capability to the Inverter)

SWITCHGEAR

2000A Power-Circsuit-Breaker Between Inverter and Step-Up Transformer, Providing Load Switching, Synchronization/Grid Connection and Fault-Clearing Functions

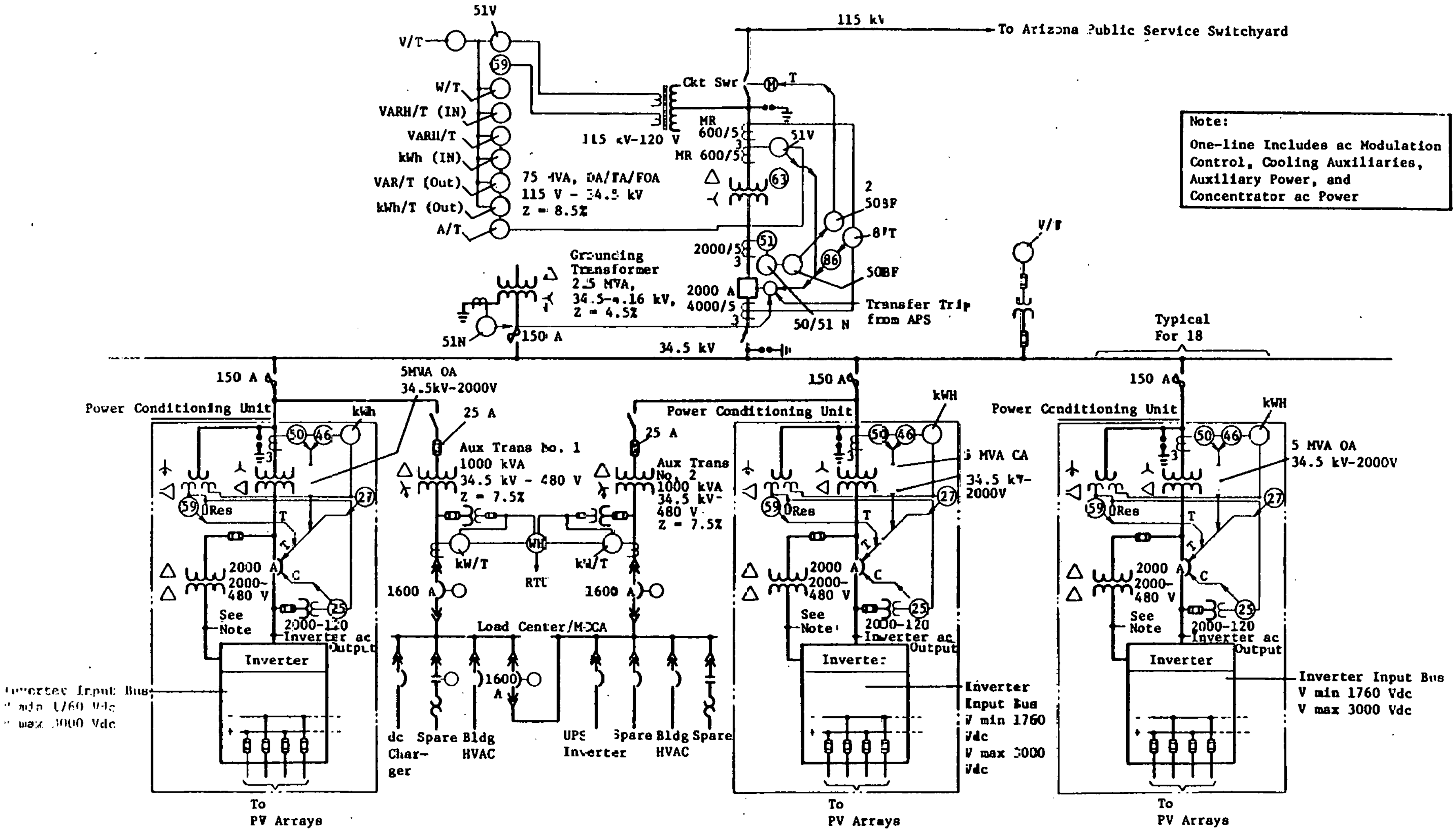

Figure II-6 One-Line Diagram of 34.5 kv Distribution System

The 34.5 kV system is grounded at a single point to eliminate pathways for circulating triple-n harmonics. The use of a bus-connected grounding transformer limits ground current to a relatively low value and also permits the intermediate high voltage bus and majority of the ac system to retain a grounded condition following opening of the main transformer low-side breaker. All surge arresters in the acES are rated for line-to-line voltage (although they are connected line-to-ground) to withstand ground fault system conditions. The grounding transformer was connected to the bus through a 150A fuse.

The acES was configured with individual feeder cables into a 115 kV utility grid-interface switchyard. This configuration provides maximum modularity in plant power output. If one power conditioning unit were lost, or if there were a cable fault between the power conditioning unit and the switchyard, only 5% of plant output would be lost.

H. INSTRUMENTATION, CONTROL AND DISPLAY SYSTEM (ICADS)

ICADS is designed to provide a plant instrumentation, control, and display system that will supply acquisition, recording, storage, and display of key system and subsystem operational data, plus automatic and manual control of those plant parameters required for successful transmission of solar-generated electric power. In the case of the concentrator array field, ICADS provides control and coordination between array field controllers (AFC) that control the operation of the PV array assemblies. For both the flatplate and concentrating CPSs, ICADS provides the coordination necessary for the data acquisition unit (DAU), power conditioning units (PCU), the ac electrical system (acES), the weather instrumentation, and the remote terminal unit (RTU). The RTU is the means of communication between the utility's dispatch control and the PV CPS.

Because of the long in-field distances involved, the components of the ICADS were connected by a system of modems employing RS-232 interfaces.

J. PLANT FACILITIES AND SERVICES (PFAS)

This section presents a summary of the facilities and services required to support operation of a PV central power Station. Plant facilities and services consist if:

- Services and utilities;
- Security and access;
- Structures and enclosures;
- O&M/Safety considerations.

Specific elements of the PFAS are summarized by an equipment delineation shown below:

Item	Description	Quantity	
		Flat Plate	Concentrator
Array Wash Water Supply	Tank - 75,000 gal.	1	--
	Tank - 37,500 gal.	--	1
	Array Wash System/Truck Wash Units	7	3
UPS Systems	20 kVA UPS	1	1
	Lead-Calcium Cells	60	60
Security and Access	Plant Fence: 6-ft High, 3-Strand Barb Wire	5.10 mi	7.12 mi
	Gate: 6 ft High, Chain Link	1	1
	Subfield Roads	15.81 mi	14.88 mi
	Field Roads	6.12 mi	7.95 mi
	Access Roads	1.84 mi	1.95 mi

Item	Description	Quantity	
	34.5 kV/115 kV Switchyard Fence, 8-ft High Chain Link	3.4 mi	3.4 mi
	Floodlights:		
	- 250 W High-Pressure Sodium Lamps	24	24
	- 100 W High-Pressure Sodium Lamps	6	6
Structures and Enclosures	Field Control Building	1,655 ft^2	1,644 ft^2
	Visitors Center	2,715 ft^2	2,715 ft^2
	Maintenance/Warehouse Building	13,200 ft^2	13,200 ft^2
Operation/ Maint/Safety	3/4-Ton Vans	1	1
	5-Ton Stake Bed Trucks	7	3
	Miscellaneous Test Equip, DVM, VI-V Testers, Oscilloscope, etc	--	--
	Miscellaneous Fire-Detection Systems and Extinguishers	--	--

Services and Utilities

PVPS services and utilities include provisions for:

- Fire Protection - Based on NFPA standards and requirement for portable extinguishers because of remote water supply;
- Sewage Treatment - Septic tank system used;
- Water Supply - Based on existing well capacities and analysis, it was recommended that no treatment or additional wells would be required;
- Array Aperture Wash Water System - Using a set of design assumptions, a scheduled washing system was devised to regularly restore array to clean condition.

Security/Access

An 8-foot-high chain link fence around the perimeter of the site will provide plant security and will prevent intrusion of large wildlife, tumbleweeds, etc. A lockable sliding gate at the main entrance controls vehicular access to the site. Both the fence and gate are of standard construction.

Within the PV site, fencing also encloses the switchyard area to prevent entry of unauthorized personnel into that restricted area.

The unpaved roads within the PV site allow nominal operating, maintenance, and security vehicle traffic, and are also capable of supporting heavy construction traffic. The perimeter roads were 54-feet wide measured from the fence line. The total 54-foot width was designed to accommodate turning radius requirements of the trucks delivering PV field components. The 39-foot central north-south road width was also based on truck turning requirements. Within the PV field, road ways separating the 5 MW subfields were 24-feet wide, being made up of 12-foot roads and 6-foot shoulders. The roadways providing access to the inverters, which are located near the center of each 5 MW subfield, are approximately 35-feet wide. This precludes shading of the arrays north of the road and provides for a 13-foot passage past the 22-foot transformer collection basin.

Access roads within the subfields were provided between the arrays to preclude shading and to permit vehicular access. It was anticipated that these will not require aggregate surfacing but will only receive the general field-leveling and smoothing, with perhaps some in-place compaction accomplished by several passes of a vibratory roller. The expense of furnishing imported surfacing for these aisleways was not warranted due to the low traffic frequency.

Structures and Enclosures - Visitors Center (optional) - A visitors center area consisting of a visitors building and parking area was located long the plant entrance road near the frontage road. The building was provided to house display and audiovisual presentations and to allow public viewing of the PV field from a roof walkway.

O&M Warehouse - A building is provided for housing of operation and maintenance equipment and for warehousing of spare parts.

PV Field Control Building - A central building was furnished at the South entrance of the PV field to house central display, control, and data acquisition equipment related to the CPS and its control interfaces with the existing facility.

Main Station Control Room Addition (APS specific) - An addition to the existing Saguaro main station control room was provided to have PV-control and data-acquisition equipment related to the control interfaces within the existing utility.

K. PLANT PERFORMANCE ESTIMATES

After reviewing the plant reference designs in the preceding sections, we now consider how a plant at the Saguaro site would perform. The annual performance estimates used a SOLMET-TMY insolation and meteorlogical data base for Phoenix, Arizona. Phoenix is located approximately 70 miles Northwest of Saguaro. The slightly lower elevation, higher smog/particulate content, and higher daytime ambient air temperatures at Phoenix makes plant performance estimates conservation for Saguaro.

The plant performance estimates were constructed from an individual subfield performance estimate by simply multiplying power and energy outputs by 20. A simplified flow chart of the module performance calculations appears in Figure II 9-1. The various parameters used in these calculations were taken from prototype module test results provided by Westinghouse (flat-plate module) and Martin Marietta (concentrator module). Details of the electrical and thermal models utilized were supplied to and reviewed by Sandia and Jet Propulsion Laboratory/FSA personnel.

Module power output, as calculated hourly from SOLMET-TMY data, was then converted to calculated ac power output by considering source circuit mismatch, joule-heating (I^2R), diode, inverter, and stepup transformer losses to be a fixed percentage of power on the dc/ac busses.

To calculate inverter losses, a linear approximation of the inverter efficiency with respect to the input voltage was evaluated in conjunction with the array current-voltage operating conditions. Then, the expected inverter efficiency was calculated as a function of dc input power from known efficiencies of in-service inverters available today in 350 Kw or larger applications.

There was no attempt made to model losses from array-soiling or tracking error nor to decrement plant power output as a result of concentrator array tracking-motor parasitic power consumption, PCU parasitics (i.e., power factor), or ICADS parasitics. These values could not be clearly defined. However, consideration was given to the 12-W average, 24-hour power drain of each concentrator array assembly. Considering 22,000 assemblies, this total annual parasitic energy consumption amounts to 2.31 GWh, or approximately 1% of plant annual output. This data is supported from field measurements taken in Saudi Arabia and at APS.

Table II-5 Summary of Annual Plant Performance

Read Insulation, Ambient Air Temp, Wind Speed	Calculate Cell Temperature	Thermal Model
	Calculate (I,V) at Max Power	Electrical Model
Fixed Losses	Calculate Module Power Output	

Module Performance Model

	Flate Plate	Concentrator
Insolation Global, Hourly	494.2 W/m^2	—
Direct Normal, Hourly	—	546.9 W/m^2
Daylight Air Dry-Bulb Temperature	25°C	25°C
Annual Plant Energy Output	246.7 GWh	283.9 GWh

III. RECOMMENDATIONS FOR FUTURE STUDY

The following section summarizes the basic output of Task IV, design problems in a PV CPS and attempts to recommend directions and approaches for future study.

A. IDENTIFICATION OF MAJOR PLANT DESIGN PROBLEMS

The design team has attempted to identify, organize, and rank the major plant design problems encountered during Tasks II & III.

1. Ranking Methodology

The design problems associated with the photovoltaic central power station may be organized into hardware, technical, and cost-related classifications . A ranking methodology has been developed to assist in estimating the relative importance of each design problem.

Numerical values were assigned to various design concerns by the design team according to criteria listed Table III-1.

Table III-1 PV CPS Design Problem Valuation Center

Classification	Value	Description
Hardware	3	- Much Development Needed
	2	- Needs Minor Design Changes or only a Limited Number of Components Exist
	1	- Mature Technology - Currently Available
Technical	3	- Solution Approach not Identified
	2	- Design Approaches Exist
	1	- Current Design is Satisfactory
Cost	3	- Major Cost Driver (Cost $0.01/Wp)
	2	- Intermediate Cost Driver ($0.005/Wp cost $0.01/Wp
	1	- Minor Cost Driver (cost $0.005/Wp)

The hardware, technical, and cost values were added for each design issue, with the resulting sum or score serving as the basis for the identification of the most critical problems. The relative importance was subsequently established by ranking the problems in order of decreasing score.

Design issues that were not applicable to one of the three classifications in Table III-1 were automatically assigned the numerical value of 1 for the particular classification of concern (e.g., the standardization of plant design with respect to A&E costs is not a hardware-related problem). This was done to ensure that the relative importance of a problem was not under estimated by neglecting a nonapplicable classification (i.e, by assigning a "0" value to the category). In addition, this scheme maintained a consistent method of evaluation, whereby the lowest and highest possible scores were 3 and 9, respectively.

2. Results

Design issues were divided into two categories. These were array concerns and balance-of-plant concerns. By ranking these items per Section 1 above, the most pertinent areas that should be investigated in future studies are sorted and prioritized. Stearns-Rogers and Arizona Public Service personnel assisted in the evaluation of design concerns from both a hardware and technical viewpoint. Cost evaluations were done by Martin Marietta Denver Aerospace. The results of the ranking are presented in Table III-2. These are listed in descending order of importance.

Table III-2 Ranking Order of PV CPS Design Problems/Issues

Score	Problem
	<u>Array</u>:
7	Development of PV Modules Capable of Providing a 30-Year Lifetime with less than 15% Degraded Power Output
6	Development of PV Modules to Meet System Voltage Isolation Requirement (of about 4200V) Without Incurring Cost Increases
5	Use of Insulated versus Nonisulated Intermodule Wiring to Lower Array Costs
	<u>Balance of Plant</u>:
8	Availability of Inexpensive High-Voltage/Current dc Switchgear for Array Field dc Power-Distribution System Protection
7	Development of Reasonable Automated Array/Panel Field Installation Techniques and Hardware
7	Feasibility of Manufacturing No. 2 AWG, 35 kV and No. 10 AWG, 2 kV Power Cable for PCU-to-Switchyard Cable Runs and Source Circuit Cabling, Respectively
6	Design of Mounting Structure/Foundations to Meet Expected Loads Using a Site Foundation Test Program
6	Design of a Less Expensive Component to Replace Array Junction Boxes While Meeting Requirements for Safe, Effective Termination of Concentrator Wiring
6	Identification of Optimal Foundation Pedestal Spacing Concentrator Field
6	Development of Fiber Optics/rf In-Field Communications for Use in Control of Concentrator Array Articulation
6	Standardization of Plant Design with Respect to A&E and Engineering Costs
5	Effectiveness of Arranging PCUs in Parallel to Reduce 34.5 kV Cable Cost
5	Development of Inverters that Provide Controlled VAR Flow Relative to Utility Transmission System Voltage Regulation Requirements

3. Discussion of Major Design Problems

In the following section, a brief explanation of the design issues listed in Table II-2 shall be discussed. First the array will be covered with its associated concerns. Secondly the balance-of-system issues will be discussed. Problems that exist are highlighted from the perspective of technical, hardware or cost for a particular design.

Array

Most array design problems relate to technical and cost issues. Module components for a central power station as described in this study need to withstand a hy-pot voltage of 4200 volts. This is 2 times the maximum expected system voltage + 1000 volts. Module design must minimize random material defects which would lower the breakdown voltage. One way of doing this would be to utilize multiple layers of different electrical insulation mediums. Design studies are needed to produce a high yield of PV modules that can meet isolation, without any substantial cost increase or loss of performance.

Utility costs being what they are, concentrating photovoltaic systems will have to prove they can be cost competitive. In general, concentrators will probably see acceptability in utility connected large load size applications. Use of concentrators in smaller applications will probably be cost prohibitive due to their size and the tracking requirements.

Flatplate technology also has performance hurdles to meet to reduce its costs per watt. However, in the case of flatplate arrays, there exists an infant market for use of the product as it goes through the evolution cycle.

Intermodule wiring costs could be reduced by using less expensive uninsulated wire. However, safety concerns for field personnel may not justify this action.

Balance of Plant

When dc ground and line faults occur in the PV field, the potential for severe damage to power cabling exists unless dc switchgear can be used to clear such faults. Unfortunately, dc switchgear (automatic contactors) that could be employed to interrupt faults on the dc bus at typical subfield design voltages and power (2000 V, 5 MW) are not available at a reasonable cost. Since fault current cannot be supplied from the PV array, conventional relaying and fault clearing via contactors on the PCU end of the bus will not work.

A major hardware problem for the balance of plant is the lack of adequately demonstrated automated installation equipment. Automated installation methods seek to avoid use of labor-intensive devices, and to use labor more productively in surveillance roles. Actual cost per benefits associated with mechanized installation methods are not known at present. Conceivable, automated installation procedures could contribute to overall reduction of plant cost once the necessary hardware has been developed.

Trade studies of power cable size indicated that No. 2 AWG/35-kV cable would be optimum for use between the PCUs and the switchyard, and that No. 10 AWG/2 kV cable would be most suitable for source circuit wiring. However, the smallest 35 kV cable commercially available at present is No. 1/0, while No. 8 AWG is the smallest 2 kV cable obtainable. This is due to a corona discharge breakdown problem that exists on smaller cables.

Drilled, cast-in-place, reinforced, concrete-pier foundations have been selected as the optimum foundation for both the flat-plate and concentrator arrays. Loading on the foundations is such that lateral wind forces will control the design of the piers. Because of the large number of foundations involved, a more detailed design study is required to reduce system cost without sacrificing the confidence level in foundation performance.

Array junction boxes were found to be one of the higher cost items in the concentrator system design, thereby providing the incentive for the development of a less expensive alternative.

A cost reduction in signal cabling could be realized with the incorporation of fiber optics or rf in-field communication links to control tracking devices in the concentrator array.

Standardization of photovoltaic plant design would certainly lower indirect engineering costs associated with engineering design for subsequent projects. However, it should be noted that total standardization of power plant design does not exist even for conventional generating systems.

Additional cable cost reductions could be achieved by wiring several power conditioning units (PCUs) in a paralleled configuration. This scheme results, however, in larger plant power losses when cable fault conditions occur due to the greater number of PCUs affected by the fault. A further investigation is warranted to determine the actual cost/benefit relationships.

No-load to full-load voltage variation over the operating range of cell temperature is about 1.5 to 1 for the photovoltaic field. The photovoltaic system must parallel a utility system having a substantially constant voltage with approximate variation of $\pm$ 5%. Depending on location of the PV CPS in the utility transmission system, the utility dispatcher may desire control of VAR out of the PV CPS. This requirement necessitates control of voltage magnitude and angle displacement (power factor) of the inverter output voltage relative to other system voltages.

B. DESIGN STUDY RECOMMENDATIONS

The primary design team recommendation concerning future studies of PV CPS design issues is as follows; use existing grid-connected photovoltaic system for conducting system-level experiments. These existing plants (e.g., APS Sky Harbor 225 kW at Phoenix, Arizona; 100 Kw at Beverly, Massachusetts) offer potential for investigating approaches to the various utility interface and array design issues.

Problems posed for central station application of photovoltaic arrays are in general being adequately approached by the various DOE photovoltaic development programs. It appears the most stringent requirement on modules will be to maintain rated power output over a 30-year design life. The use of electrically live head sinks appears solely an institutional issue. These are no inherent technical problems, only considerations of cost advantages and utility safety. Similarly, for non-insulated intermodule wiring, the issues are largely institutional, because utilities are not required to observe NEC regulations in CPS designs.

By far, the most important areas for future study exist at the system level. Most balance-of-plant components, i.e., mounting structures, cables, transformers, etc, are rapidly approaching design maturity. Large, high-power inverters are not completely ready for implementation. The problem for central station designers becomes one of configuration. The designs presented herein are to be considered a starting point for future optimization and refinement.

Contacting and switching of high voltage dc currents is just starting to be addressed by the switchgear manufactures. The switching of dc has unique problems of arcing that do not allow for an easy transition from ac switch gear.

One of the biggest design problems encountered was how to protect the dc bus in the event of a cable fault. Several alternatives to extensive automatic contactors exists. One possibility would be to use a battery to feed fault current over and above the fault contribution of the PV array, to allow the use of a conventional 50/51N relay to open contactors and clear the fault. The battery could be located at the PCU and could supply the required fault current instantaneously without the need for many cells. Another possibility for clearing dc faults for concentrators would be to use the detracking capability of the concentrator array to remove all current from the dc bus. Using existing drive mechanism slew rates (27.7 deg per min) and measured module power output profiles for various degrees of off-normal tracking, it was predicted that a dc fault could be 93% cleared in less than four minutes. This may or may not be a sufficient fault clearing time for this type of fault; however, the capability for faster slew rates could easily be provided. Both of these approaches could be evaluated at the APS Sky Harbor 225 kW photovoltaic project.

Concerns of cost savings to be gained from automated array installation were discussed in a previous study report.[5] For the central station designer the decision to use automated techniques must be based on the answers to these questions:

- What are the overall cost savings over conventional installation?

- Who will pay for the installation equipment, assuming it has been demonstrated—the general contractor, the utility, or the A&E?

The study of automated array installation should focus on obtaining reasonable estimates of the development costs of installation equipment. This will require that detailed designs of such equipment closely tie to the development of automated techniques themselves.

During the course of the detailed plant design, it was found that certain cable in a specific size was not available (e.g., 34.5 kV ac cable in the No. 2 AWG size). However, the technology to produce those items is certainly available. Manufacturers will likely produce them whenever there is a demand. A minor follow-on activity may be of value to confirm this assumption.

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5 "Automated Installation Methods for PV Array". Final Report, Burt Hill Kosar Rittleman Associates, SAND81-7192.

The decision to implement the existing site soils data, which recommended ignoring the top 0.5m of soil as a lateral bearing surface, resulted in concrete-pier depths for the array mounting structures that may, in fact, be overdesigned. For any system designer, it is recommended that a simple site foundation testing program be implemented before foundation erection begins, and that the objective of such a foundation testing program would be to arrive at an optimum foundation depth for both edge-of-field and interior pedestals consistent with test results. Such a program would consist of: pouring several foundations of differing depth, diameter, etc; applying measured loads to failure; tabulating the results, and; making a decision based on a predetermined safety factor.

The cost of the concrete foundations (e.g., flat plate array $10.6M total/$3.7M material) provides incentive for using a steel pipe pedestal embedded in a poured-in-place concrete foundation. The material cost can be cut by almost 33% by use of this concept (Fig. III-1). Moreover, the labor used in erecting and removing above-grade forms is eliminated, cutting costs even further. An evaluation program should be established to build several test pedestals of this type. A program could investigate actual labor/material savings and determine load carrying and reliability characteristics.

As stated earlier, a new approach to simplified concentrator array junction boxes is needed. It may be possible to refine requirements for concentrator array electrical terminations to allow a less expensive plastic enclosure with an insulated stud mounted to the array pedestal, eliminating the J-box foundations. The concept should be reviewed by A&E personnel as utility safety and maintenance personnel for general acceptance.

The concept of "teeing" together several PCU outputs to reduce total ac cable lengths should be evaluated by trading off the advantages of less cable and cable installation cost, against the disadvantages of increased number of cable terminations, increase cable size, increased switchgear and grounding transformer size, and the loss of field power-output modularity in the event of a 34.5kV cable fault.

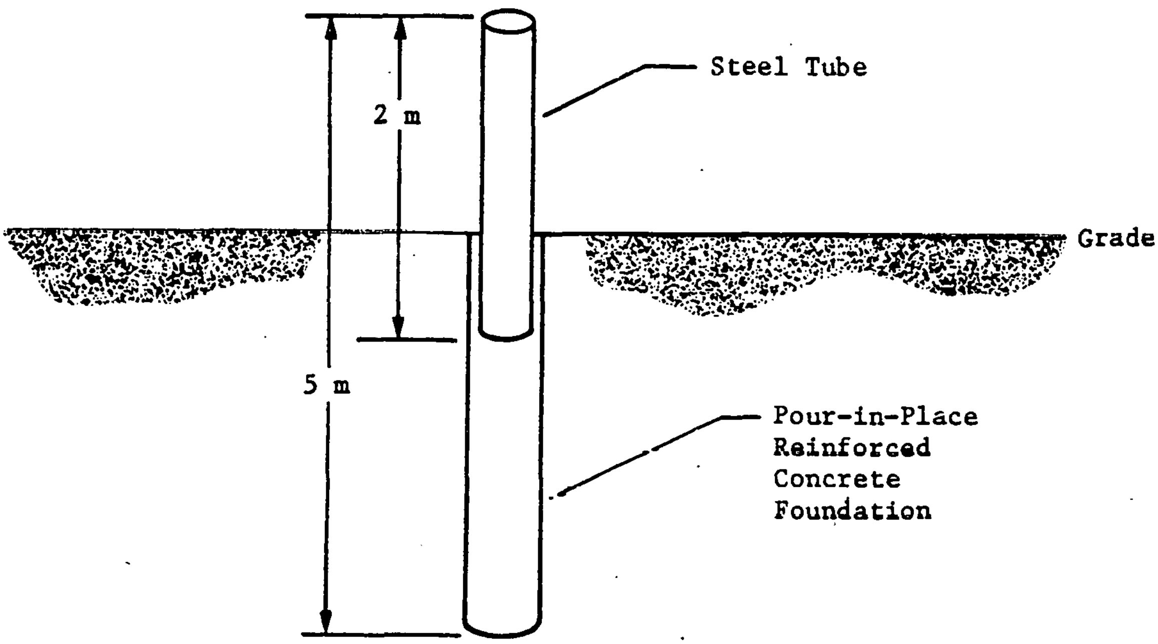

Figure III-1 Steel-in-Concrete Pier Concept

A consideration of the costs of signal wiring for a 100 MW CPS indicates that an investigation of a low-cost rf receiver functioning as a frequency-shift-keying (FSK) data link is justified. Should such a unit be manufactured as an integral part of the array controller, it would result in a slight increase in the cost of the controller, but could also result in a substantial reduction in the cost of signal wiring (approximately 2% of total cost).

Areas of investigation should include frequency band selection, data rates, noise and error effects, antenna size placement, single-or multiple-channel requirements, minimum part count designs, design reliability with time, and stability with line and temperature, sensitivity, etc.

C. SUBJECTS FOR FUTURE INVESTIGATION

VAR Generation

Large power generating systems must supply the reactive current component as well as the real component. This reactive power (KVAR) is not a revenue producing element, because only real power can be billed to the customer. Reactive power costs utilities because of the I^2R losses in the transmission lines. The requirement to generate this reactive component also makes voltage regulation of the line much more difficult.

Large cogenerating inverters that can supply reactive as well as real power need to be developed. These inverters would be particularly beneficial for supplying large capacitive components (absorb VARS) that are required during the times of low power demands. If PV inverters were developed with this capability, the PV system would be much easier to integrate into the general utility control systems.

I-V Testing

The most important quantitative test that is performed periodically is the PV I-V test. Because this test simply applies a variable-current load to the I-V lines and measures the resultant bus voltage, it is logical that the PV inverter is a load that could be used for this function.

Large inverters need to be developed that can be made to operate from no-load to close to short-circuit current conditions. The inverter should automatically vary the load through the full I-V current range, and at the same time, record the PV bus voltage and current readings. It would also be desirable for it to have its own microprocessor and software with a built-in capability of generating the complete I-V curve normalized to a standard set of reporting conditions.

D. UTILITY RECOMMENDATIONS

In this section, the utility team members have addressed concerns covering key technical, economic, and institutional issues surrounding the PV CPS within the utility framework. In general, technical issues are viewed as less important than economic questions. PV technology has been proven to work; the only barrier to its widespread use is cost.

PV Plant Rating

PV plants cannot be rated in the same manner as conventional plants. This is not a vitally important issue, because the PV plant's output can be described adequately, although not concisely. However, the question warrants further effort to standardize the rating approach.

System Stability Enhancement

Photovoltaic plants could demonstrate the ability to improve the stability of the utility power system. As an example, a typical system disturbance might be the loss of a key transmission line between two areas of high generation. In this case, fast-acting inverter controls could rapidly reduce power output to maintain the proper level and be ready to increase generation as soon as the disturbance has passed. A conventional unit in the same situation would trip off-line as a result of overspeed controls and would, therefore, be completely lost until it could be restarted and resynchronized. Also, in the case of PV plants, if the inverters can be controlled fast enough, they may be used in this same fashion to help damp oscillations in the system.

If the PV plant were located in an area of deficient generation, it might still provide some benefits during this typical disturbance. Although power output from the PV CPS could not be increased because of the characteristics of the PV cells, the inverters might be able to quickly increase VAR production to support a sagging system voltage.

Again, this capability is not vital to acceptance of PV, but if it is available, cost savings may result in other parts of the utility power system. A higher allowable energy cost for the PV plant would result.

Evaluation of this capability would require a study of the capabilities of the inverters, plus power system studies.

Additional studies of transients in PV plant output caused by intermittent cloud cover are needed. In the case of central-station PV, the utility dispatcher may see 100-200 MW of power going on-line, then off-line etc. It should be determined whether this is really a problem, and if so, how to handle it.

Since the PV output does not match the load profile on the utility system, the utilities desired studies on how to integrate storage at reasonable cost with PV.

The economic concerns from the utility framework include the magnitude of O&M costs, plant lifetime, financing, and a recommendation for making a detailed cost account study of the data developed under this contract.

<u>O&M Costs</u>

An estimate of O&M costs is required to properly assess the total life-cycle cost of the plant. Tradeoff studies also need to be made between annual O&M costs and initial capital cost.

<u>Plant Design</u>

An evaluation of lifetime of the plant and degradation of output (if any) over time is needed to properly assess the actual cost of the plant

<u>Financing</u>

Follow-on studies of plant economics are needed that consider time, financing arrangements (i.e., third party), etc, to isolate the best near and long term approaches to plant construction.

Since economics is an important issue, valuable follow-on efforts involve studies of way to reduce plant cost and increase output. Two examples are:

- Use of advanced, higher efficiency components;
- Investigation of new array mounting approaches including the use of flat plate mounting structures as wire raceways.

A potentially valuable, or at least interesting, follow-on effort would be to review cost accounting, and for each plant item, assess the possibility of cost reductions. Reductions could result from future decreases in equipment costs, or by the use of equipment with reduced (but still acceptable) capabilities. The value in identifying specifically where cost reductions are possible, especially in the balance-of-plant areas, is to give a more realistic estimate of the "ultimate" cost of PV plants.

The following points were identified as important issues from the utility viewpoint.

Water Use

The water requirements of PV plants are significantly lower than for conventional plants. This is a notable advantage in the deserts of the Southwest. However, additional follow-on work may be worthwhile to see if water use can be reduced even more. If less cleaning is required, savings in O&M costs would also result.

Land Requirements

This study reemphasized the high land requirements for a relatively small amount of electrical power produced. This makes questionable location of PV plants near the load; land near major cities will be too expensive. However, some follow-on work to study the possibility of sites in exclusion areas around airports and nuclear plants would be valuable.

Summary

In summary, the utility recommendations for future work identified several areas of importance: economic issues (since economics is a factor limiting widespread use of PV); capabilities of inverters; reliability of PV components; expected service life of PV systems; and operational requirements (How many and type people are required to operate a PV site per megawatt?).

IV. ECONOMIC CONSIDERATIONS

A. COST ANALYSIS

This section reviews construction costs for the 100 MW flatplate and concentrator PV central power station reference plants and major plant cost drivers. It includes a discussion of technology development and other nonrecurring costs.

1. Plant Construction Cost Estimates

A construction cost estimate was developed for both types of PV plants, using the detailed design results from Task II and III, including: the hardware breakdown structure (HBS); system, subsystem, and component specification; plant design drawing; and the construction schedules.

Cost are expressed in 1982 dollars,and including project expenses ranging from initial project development through plant commissioning. Plant design is based on current technology hardware and construction methods for all components except PV arrays and inverters. Plant construction completion dates are presumed to be in the 1986 to 1990 time frame. Projected technological development for PV arrays and inverters makes the task of estimating costs for these items very difficult, so a range of parametric values was used. Parametric values for the PV arrays and inverters are based on expected mid and long-term projections as seen in the literature and as expressed by various experts and related hardware manufacturers.

Other costs are developed using established and reliable cost sources including catalog and manufacturer quotes, current costs estimating manuals, and standard construction labor, equipment, and material estimating methods. Engineering, management, and other indirect costs are based on labor-loaded task breakdowns, current governmental requirements, and local site specific conditions. Every effort has been made to include all relevant items and accurate costs, consistent with the level of detail in the design.

A detailed cost breakdown structure (CBS) was used to accumulate the cost data, and provides an excellent mechanism for performing cost analysis, cost trade studies, and sensitivity analysis. A list of the major accounts is shown in Table IV-1.

Table IV-1 Cost Breakdown Structure, Major Accounts

1000		Project Development
	1100	Management Services
	1200	Engineering Services
	1300	A&E Services
	1400	Testing Programs
	1500	Applications & Approvals
	1600	Construction Management
2000		Project Construction
	2100	Land & Taxes
	2200	Site Preparation & Improvements
	2300	Non-Building Foundations
	2400	PV Systems
	2500	Building & Enclosures
	2700	Operation & Maintenance Equipment
	2900	Adjustments & Contingencies

The results of the cost analysis are shown in Table IV-2. This table shows the total construction costs relative to the parametric values. The last line is equivalent to an effective balance of plant cost, with no value assigned to the PV arrays or inverters, and no corresponding taxes or other proportional array and inverter related costs.

2. Analysis of Costs

A review of the detailed cost sheets provides a list of the major cost drivers for each type of plant. The detailed cost sheets (including Appendix of both Volumes II and III) list each line item along with breaking out the material, labor, and other (equipment/subcontract for each. All burdens, overhead charges, and fees are contained in those figures. Since some of the costs, such as taxes, depend on the value of the parametric costs, construction costs determined at the lowest parametric values will be used for cost analysis purposes.

Major account totals for both plants are shown in Table IV-3.

Flat Plate Plant Cost Analysis

Even at $1.00/Wp, the cost of the PV arrays is clearly the single largest cost driver, amounting to over 55% of total plant cost.

Table IV-4 shows the major cost drivers for the flat-plate CPS plant. This list comprises roughly 20% of individual cost-account line items, but amounts to 94% of total plant cost.

Table IV-2 CPS Plant Construction Cost Estimates

Parametric Cost Scenario	Flat Total Plant Cost* ($M)		Concentrator Total Plant Cost* ($M)	
	1982 $	1980 $	1982 $	1980 $
A (4.00)	482.8	408.2	505.0	427.0
B (2.50)	328.3	277.6	350.5	296.4
C (1.50)	225.3	190.5	247.5	209.3
D (3.70)	451.9	382.1	474.1	400.9
E (2.20)	297.4	251.5	319.6	270.2
F (1.20)	194.4	251.5	319.6	270.2
G (3.55)	436.5	369.1	458.7	387.9
H (2.05)	282.0	238.4	304.2	257.2
I (1.05)	179.0	151.4	201.2	170.1
- (0)	70.8	59.9	93.0	78.6

* - Rounded to Nearest $100,000

  - Total ($/Wp) = Inverter + Array

By breaking the total plant costs down into the generalized categories shown in Table IV-5, we can get another view of how costs are distributed, and which systems categories can benefit most from targeted cost-reduction efforts.

Out of these general groupings, the two largest cost categories are PV arrays and power distribution. Even excluding the cost of the arrays, these two categories are still the largest at $14.9 M and $24.6 M, respectively. Of interest is the fact that the parametric costs of the arrays (and inverters) are based on changing their cost. In using these parametric values, no account is made for increased efficiency per array due to technology improvements. What is generally expected to happen is that both manufacturing costs will come down and module efficiency improvements will continue to be incorporated as available. Naturally, as either or both of these improvements evolve, the number of arrays required for a given power plant will decrease. Any reduction in arrays will directly affect the cost of such systems. In addition, the reduction will also have favorable influence on other areas such as the PV field (i.e., land costs, grading, etc.).

A doubling of array efficiency roughly would reduce the balance-of-plant costs by about $22 M (from $74 M to $52 M, a reduction of about 30%).

Technological advances and cost reductions are certainly expected in other areas of plant design as well, so that in the long term, construction costs for flat-plate central power plants can be expected to be in the range of from $1.40 to $1.50 per peak watt in 1983 dollars. This depends on achievement of high-efficiency, low-cost solar components, and economics affected by production-learning and plant-design standardization.

Account Number	Account Description	Account Total Cost (1982 $)					
		Flatplate	A	B	Concentrator	A	B
1000	Project Development						
1100	Management Services	2,024,000	1.1	2.7	2,227,000	1.1	2.3
1200	Engineering Services	5,019,000	2.8	6.8	6,684,000	3.3	6.9
1300	A&E Services (Inc in 1200)						
1400	Testing Programs	33,000	0.0	0.0	33,000	0.0	0.0
1500	Applications & Approvals	756,000	0.4	1.0	710,000	0.4	0.7
1600	Construction Mgmt	649,000	0.4	0.9	609,000	0.3	0.6
2000	Project Construction						
2100	Land & Taxes	5,226,000	2.9	7.1	5,765,000	2.9	6.0
2200	Site Prep & Improvments	5,499,000	3.1	7.4	7,658,000	3.8	8.0
2300	Non-Building Foundations	11,050,000	6.2	14.9	7,572,000	3.8	7.8
2400	PV System	135,532,000	75.7	--	153,212,000	76.2	--
	(PV Arrays)	(100,000,000)	--	--	(100,000,000)	--	--
	(Inverters)	(5,000,000)	--	--	(5,000,000)	--	--
	(Balance of Account)	(30,532,000)	--	41.3	(48,212,000)	--	50.1
2500	Buildings & Enclosures	669,000	0.4	0.9	669,000	0.3	0.7
2700	O&M Equipment	922,000	0.5	1.2	832,000	7.6	15.8
2900	Adjustments & Contingencies	11,572,000	6.5	15.6	15,203,000	7.6	15.8
Total		178,951,000	*	*	201,174,000	*	*

A = % of Total Plant Cost
B = % of Plant Cost less Arrays & Inverters

* Columns May Not Total 100% Due to Rounding

Table IV-3 Major Account Cost Totals Array at $1.00/Wp, Inverter at $0.05/Wp

Table IV-4 Flat Plate CPS Cost Drivers

Account Number	Description	Cost (1982 $)	
1200, 1300	Engineering & A&E Services	5,019,000	
2111	Land	1,058,000	
	- (PV Area)		(500,000)
	- (Balance of Plant)		(558,000)
2112	Taxes		
	- Property Taxes	3,461,000	
2214	Clear & Grub	1,610,000	
2215	Grading & Stabilization	1,316,000	
2216	Trenching & Backfill	1,264,000	
2218	Paving & Roads	977,000	
2300	Non-Building Foundations		
	- Array Foundations	10,057,000	
2401	Array Installation		
	- Erect & Secure	4,150,000	
	- PV Array (at $1.00/Wp)	100,000,000	
2402	Power Conditioning	6,065,000	
	- (Inverters at $0.05/Wp)		(5,000,000)
	- (Balance of Account)		(1,065,000)
2404	Electrical Systems		
	- DC Distribution Boxes	2,861,000	
	- 2" Weather Heads, RGS, RGS Elbows	2,652,000	
	- dc Power Cabling		
	#8 AWG, 2/c, 2kV	7,967,000	
	#4 AWG, 3/c, 2kV	1,418,000	
	- ac Power Cabling		
	34.5 KV, 3/c, #1/0	1,270,000	
	- Trench Planking	3,854,000	
2407	ICADS	924,000	
2911	Labor Adjustment For Remote Location	2,338,000	
2920	Contingency	8,879,000	
	Total	167,737,000 - (93.7% of Total Plant Cost)	

Table IV-5
Flat Plate CPS Total Plant Cost Alternative Generalized Cost Categories

Category	Includes	Cost (1982 $)
Management	- Program Management, G&A - Construction Management	2,763,000
Engineering	- Preliminary & General Engineering - A&E Design Services	5,019,000
Ancillary Expenses	- Testing - Application & Approvals - Taxes	4,958,000
Misc Costs	- Land (Balance of Plant) - Utilities - Roads - Visitor Center - Warehouse - Security - Maint. Tools & Equip.	2,421,000
PV Arrays	- Arrays ($100M) - Installation - Foundations	114,921,000
Power Distribution	- Trenching & Backfill - Distribution Boxes & Foundations - Wiring, Cabling, Splices, Switchgear - Planking	24,555,000
PV Field	- Land (PV Field) - Clear & Grub - Grade & Stabilization - Fences & Gates - Lighting	4,382,000
Power Conditioning	- Misc Foundations - Transformers - Inverters ($5M)	7,012,000
Field Control	- Field Control Wiring - ICADS - Buildings	1,436,000
Allowance	- Adjustments - Contingencies	11,572,000

Concentrator Plant Cost Analysis

As with the flat plate plate plant, the largest single cost item in the concentrator plant is the cost of the arrays (at $1.00/Wp), which is a little less than 50% of total plant cost. Table IV-6 shows the major cost drivers for the concentrator CPS plant. Comprising roughly 20% of the individual cost-account line items, the total value of this list of cost drivers amounts to 95% of the total cost of the plant.

A review of Table IV-6 shows array J-boxes with foundations to be the highest single cost item, and the array foundation to be the next highest. These two items account for 6.6% and 3.6% of total plant cost, respectively, and 13.7% and 7.6% of the balance-of-plant cost, respectively. None of the items in the the table comprise a major portion of plant cost, so that cost-reduction efforts, in terms of construction techniques, materials, and suppliers, can be pursued effectively for many items. As with the flat plate plant, most of the cost drivers have to do with field related items.

Table IV-7 shows concentrator plant costs broken down into alternative generalized categories, providing another view of plant cost distribution. An analysis of these categories shows how development and design efforts in one area can affect costs in that area, plus costs in other areas.

As with the flat plate plant, the parametric costs of the PV arrays and inverters are based on changes in production cost, holding efficiency constant. Changes in array efficiency will have marked effects on plant costs, because, for a given plant power rating, the number of arrays (along with corresponding field-and power-distribution requirements) is directly proportional to changes in array efficiency. Looking at Table IV-7, we see that, next to the cost of the PV arrays, a tremendous cost is involved with power distribution, comprising over 21% of the total plant cost alone. Clearly, efficiency improvements will play a significant role here.

Table IV-6 Concentrator CPS Cost Drivers

Account Number	Description	Cost (1982 $)	
1200, 1300	Engineering & A&E Services	6,684,000	
2111	Land	953,000	
	- (PV Area)		(733,000)
	- (Balance of Plant)		(220,000)
2112	Taxes		
	- Contractor's Tax	924,000	
	- Property Tax	3,888,000	
2214	Clear & Grub	2,306,000	
2215	Grading & Stabilization	1,562,000	
2216	Trenching & Backfill	2,290,000	
2218	Paving & Roads	1,051,000	
2300	Non-Building Foundations		
	- Array Foundations	7,278,000	
2401	Array Installation		
	- Erect & Secure	2,712,000	
	- PV Array (at $1.00/Wp)	100,000,000	
2402	Power Conditioning	6,065,000	
	- (Inverters at $0.05/Wp)		(5,000,000)
	- (Balance of Account)		(1,065,000)
2404	Electrical Systems		
	- DC Distribution Boxes	2,725,000	
	- Array J-Boxes W/Foundation	13,200,000	
	- DC Power Cabling		
	#8 AWG, 2/c, 2kV	4,581,000	
	#4/0 AWG, 3/c, 2KV	3,445,000	
	- AC Power Cabling		
	34.5 KV, 3/c, #1/0	1,499,000	
	- 600 V, 2/c, #8 W/GND, Armored	4,881,000	
	- Instrumentation/Field Cabling		
	- 1-TSP #16 AWG, Armored	1,031,000	
	- Cabling/Wire Terminations	1,043,000	
	- Trench Planking	6,121,000	
2407	ICADS	1,329,000	
2911	Labor Adjustment For Remote Loc	3,038,000	
2920	Contingency	11,663,000	
	Total	190,269,000 = (94.6% of Total Plant Cost)	

Table IV-7 Concentrator CPS Total Plant Cost Alternative - Generalized Cost Categories

Category	Includes	Cost (1982 $)
Management	- Program Management, G&A - Construction Management	2,836,000
Engineering	- Preliminary & General Engineering - A&E Design Services	6,684,000
Ancillary Expenses	- Testing - Application & Approvals - Taxes	5,555,000
Misc Costs	- Land (Balance of Plant) - Utilities - Roads - Visitor Center - Warehouse - Security - Maintenance Tools & Equip. - Equipment	2,421,000
PV Arrays	- Arrays ($100M) - Installation - Installation - Foundations	109,990,000
Power Distribution	- Trenching & Backfill - Distribution Boxes & Foundations - Wiring, Cabling, Switchgear - Planking	42,420,000
PV Field	- Land (PV Field) - Clear & Grub - Grade & Stabilization - Roads - Fences & Gates - Lighting	5,723,000
Power Conditioning	- Misc Foundations - Transformers - Inverters ($5M)	7,362,000
Field Control	- Field Control Wiring - ICADS - Buildings	3,402,000
Allowance	- Adjustments - Contingencies	15,203,000

For example, using a long-term projection of a 100% increase in array efficiency, effectively halving the numbers of arrays, array foundations, and field costs, and reducing other indirectly related costs such as taxes, engineering, and others, the cost of a 100 MW concentrator plant (at $1.00/Wp array cost) can be reduced by roughly $30 M. This is 15% of total plant cost, and over 30% of balance-of-plant costs.

Allowing for cost reduction in other areas because of design and technology improvements, and capturing cost improvements as a result of production and construction learning, we might expect large concentrator CPS plants in the long run to cost around $1.55. to $1.65 per peak watt (1982 dollars).

B. ECONOMIC ANALYSIS

Through construction costs are an important parameter, the true value of a project can only be measured in terms of long-run energy costs by use of a required-revenue method. This determines a yearly cash flow, taking into account construction time-period costs, allowance for funds, operation and maintenance cost, escalation for capital and O&M, tax effects, cost of money, and other factors. These cash flows are then discounted back to a base year to derive a present value. This is then levelized over the life of the plant to yield an even yearly expense with a present value equal to the present value of the previously determined cash flows. This yearly expense is then divided by the yearly energy output of the plant to determine levelized bus bar energy costs (BBEC). The resulting BBEC can then be compared to BBEC values for alternative energy conventional energy (coal, oil, nuclear) plants.

1. Assumptions

The approach taken for the analysis was to use economic data that corresponded as closely as possible to Arizona Public Service factors. As such, the financial, cost, and economic factors used in the BBEC analysis are shown in Table IV-8.

Operating and maintenance costs for both types of plants were determined from engineering estimates,

Table IV-8 Financial Parameters Used in BBEC Analysis

Capitalization	Fraction	Rate	Weighted Rate
Bonds 48%	14%		6.7%
Common Stock	40%	18%	7.20%
Preferred Stock	12%	14%	1.68%
Cost of Capital	100%		15.60%

Tax Structure	
Federal Tax	46.00%
State Tax	5.40%
Composite Tax	48.92%
Property Tax & Insurance	2.3%
Investment Tax Credit	10.00%

Financial Factors	
After Tax Cost of Capital	12.31%
Discount Rate	15.60%
AFUDC Rate	12.31%
Book Depreciation	30 Year/ Straight Line
Tax Depreciation	15-Year/ ERTA-TEFRA
Residual Value	0
Plant Life	30 Years

Economic Factors	
Capital Escalation	8%
O&M Escalation	8%
GNPD	8%

and from past study and field experience with PV and solar thermal plants. These cases were run for each PV plant type (see Table IV-9).

Table IV-9 Comparison of Operating and Maintenance Costs

Scenario	Parametric Values (1982 $/Wp)		Year of Commercial Operation
	Array	Inverter	
A	3.50	0.50	1986
B	2.00	0.20	1988
C	1.00	0.05	1990

2. BBEC Analysis Model

The model used to perform the analysis is a Martin Marietta Aerospace program called SCREAM that follows the revenue requirements approach outlined.[6] SCREAM takes the inputs from Table IV-8 and provides the user with cash flow summaries, depreciation summaries, etc, as well as fixed charge rates and bus bar energy costs.

3. BBEC Results

The results of the energy cost analysis are shown in Table IV-10 and are plotted in Figures IV-1 and IV-2. Obviously, energy costs are highly dependent on array and inverter costs, and on the total amount of energy produced by the plant. In this instance, for equivalent arrayed-inverter prices, even though initial construction costs are higher for the concentrator plant, the levelized bus bar energy cost is lower than the BBEC for the flat plate plant.

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6 J. W. Doane: "The Cost of Energy from Utility-Owned Solar Electric Systems; A Required-Revenue Methodology for ERDA/EPRI Evaluations." Report No. ERDA/JPL-1012-76/3, Jet Propulsion Laboratory, June 1976.

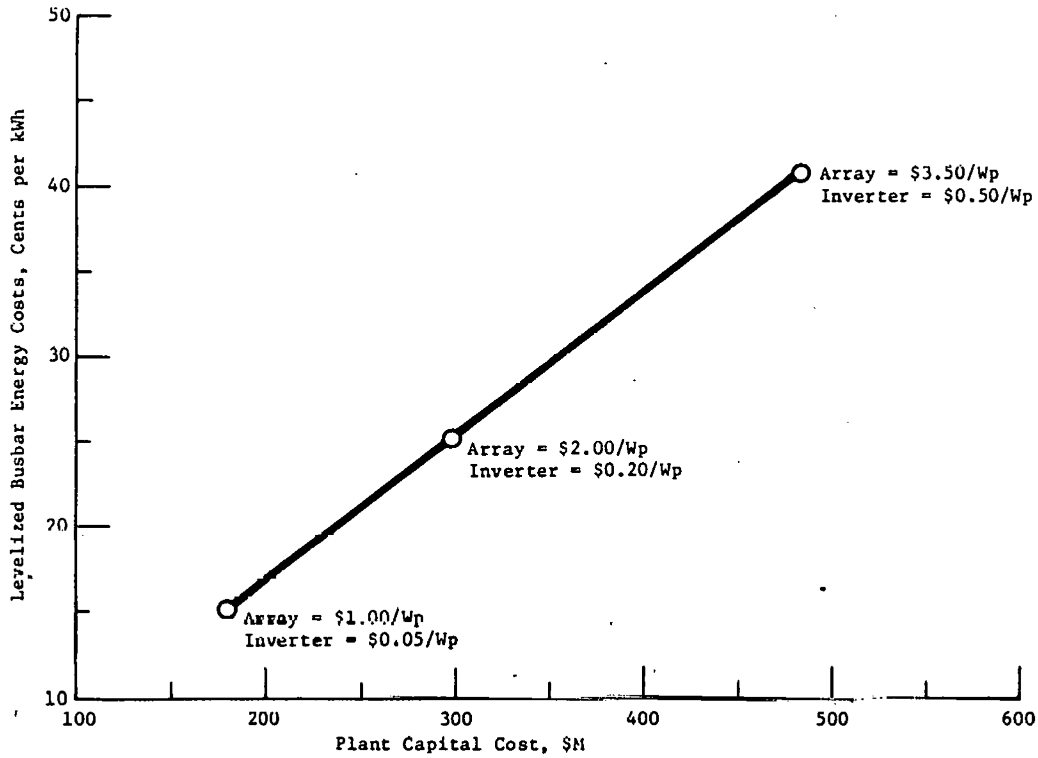

Figure IV-1 Flat Plate Levelized Busbar Energy Costs, 1982 Dollars

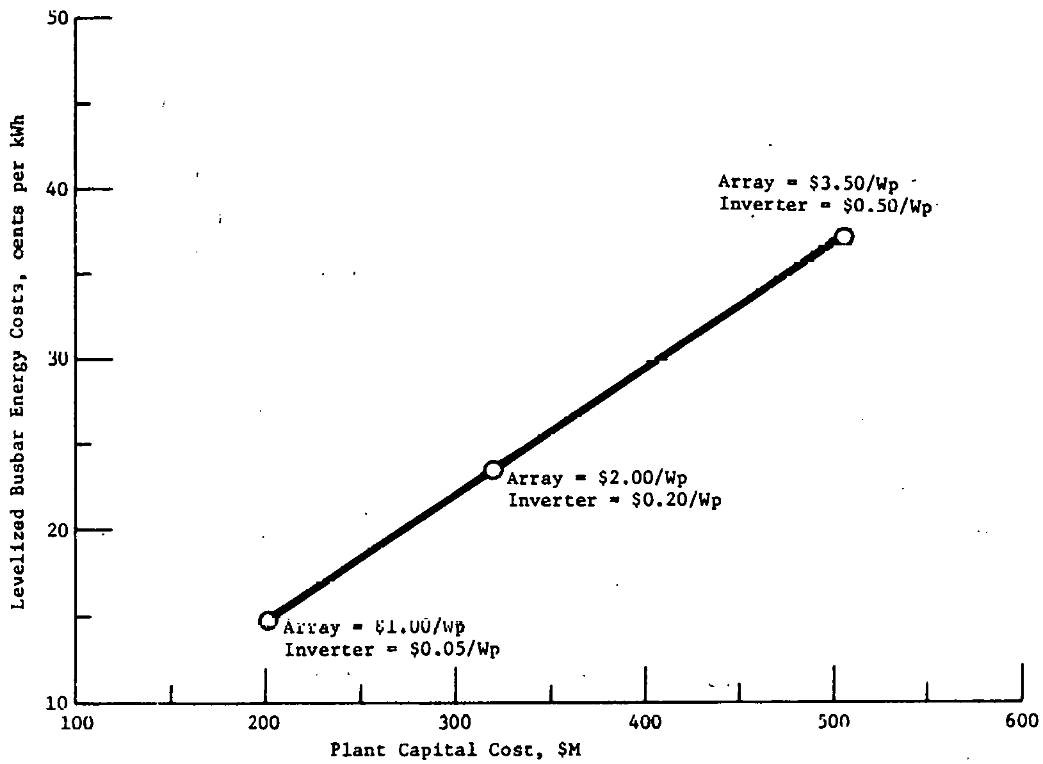

Figure IV-2 Concentrator Levelized Busbar Energy Costs, 1982 Dollars

If we look at the expected long term costs for PV plants as discussed earlier, we begin to see what the long-term BBEC lower bound might be. Using a plant cost of $1.40/Wp and $1.55/Wp for the flat plate and concentrator plants, respectively, and 100 MW nominal plant rating, and the same economic and yearly energy values used before, SCREAM was run assuming a 1994 plant completion date. The results are shown in Table IV-11, and are representative of the lower BBEC bound we might expect PV power plants to reach.

Table IV-10 $\overline{\text{BBEC}}$ Analysis Results

	$\overline{\text{BBEC}}$, ¢/kWh, 1982 $	
Scenario	Flat plate	Concentrator
A	41.00	32.27
B	25.30	23.62
C	15.23	14.88

Table IV-11 Long Term $\overline{\text{BBEC}}$ Outlook (1982 Dollars)

	Total Plant Cost ($/Wp)	$\overline{\text{BBEC}}$ (¢/KWh)
Flat Plate	1.40	12.98
Concentrator	1.55	12.54

4. Conventional Plant BBEC Comparison

The above values are useful for comparing between each other, but how do they relate to conventional energy options?

To answer this question an analysis was done to determine the levelized value of conventional energy displayed by the two reference PV plants. Only energy displacement value was considered, since there is some question how much capacity credit would be expected. Fuel Oil No. 6 was chosen, with the following related parameters:

Fuel cost:	$7.49/Barrel
Fuel Heat Rate:	11,000 BTU/kWhe
Fuel Inventory:	90 Days
Time Frame:	1994

Analysis shows that at $35/barrel for oil (1982 dollars) escalated at 3% real for 30 years at an annual inflation rate of 8.5% and a discount rate equal to 12.5%, the BBEC for fuel above would be 22c/kWhe. Therefore, at the lower array and inverter parametric cost levels, the BBEC of PV energy is justifiable as compared with some conventional energy (high fuel cost) sources.

5. Other Considerations

In areas of the United States where insolation levels are higher, or where conventional energy costs are higher, or both, PV energy may become competitive even sooner. An if some capacity value can be assigned, PV energy will have even more opportunity to displace conventional fuels.

In foreign markets where energy costs are a factor of two or three times the cost of U.S. energy, PV can be competitive as early as the late 1980s. This assumes, of course, that development work will continue at current or even accelerated rates, that projected technology advances do indeed occur, and that regulatory and other issues can be satisfactorily resolved.

Certain factors can have multiple effects toward encouraging PV development and commercialization. One factor that probably has the strongest impact is tax credits. Energy and investment tax credits have the effect of lowering the capital cost by having the federal or state government pay a portion of the cost. By reducing the cost of a plant (and the resulting BBEC) commercialization is encouraged, production and construction learning take place and reduce these costs, thereby accelerating the commercialization process even more.

Utilities typically are not fully able to capture the effects of these tax credits. Specifically, utilities are not allowed to claim energy tax credits. But third-party investors, with the help of accelerated depreciation and other financial mechanisms, can potentially receive a return on investment that is acceptable, given the level of risk involved.

Third-party, or project financing, is currently a real option. The United States' federal and state governments have attempted to foster development of all renewable technologies through tax incentives and legislative initiatives, hoping to stimulate the market sufficiently to reduce costs. The intent is to produce long-term economic alternatives to fossil fuels.

Specifically, there is presently a 15% federal energy tax credit (in addition to 10% federal investment tax credits) for investment in solar energy equipment. This credit is not available to utilities. Similarly, all machinery and equipment (again, not owned by utilities) is eligible for a 5-year depreciation period for tax purposes. Finally, the Public Utility Regulatory Policy Act of 1978 (PURPA) mandates that public utilities must purchase electricity from private energy producers, with the price based on the utility's marginal cost of energy production. Further, PURPA exempts such small power producers from most utility regulations.

An example of a project financing structure is shown in Figure IV-3. A partnership, consisting of a general partner and one or more limited partners (all of whom are corporate entities) is formed to build and own the plant. This partnership is commonly termed the "third party" in the transaction.

The partners would contribute 15 to 30% of the capital required to construct the plant, and would receive in return all tax benefits and any profits (after debt repayment) from the project. A consortium of lending institutions would provide the remainder of the project capital requirements as debit, to be repaid as a level principal repayment sinking fund over 15 to 30 years. The debt would be limited, or nonrecourse, to the partners. In other words, the debt would be secured solely by the project assets (the plant) and the project revenues. Project revenues result from a purchase contract between the partnership and the utility, such as a take-and-pay (take-if-tendered) contract in which the utility agrees to purchase all energy and capacity delivered by the facility at an agreed upon price. If no energy is delivered, no payment is required. The final component of the structure is an operating and maintenance contract.

One of the key issues is the allocation of the risks associated with the project, particularly in light of the use of a new technology. All of the project risks—completion, market, performance, force majeure—must be allocated and covered to satisfy the lending institutions requirement of "guaranteed" debt service. For example, the completion risk might be covered by firm price/schedule bids by the equipment suppliers and an equity reserve account to cover cost overruns. The market risk (i.e., the risk that the project could not sell its electricity) would necessarily be accounted for with the contract with the utility. Performance risk could be alleviated by limited-performance guarantees by equipment suppliers, but may have to be borne by the third party after 3 to 5 years of operation. It would be necessary to insure against force majeure through conventional insurance sources.

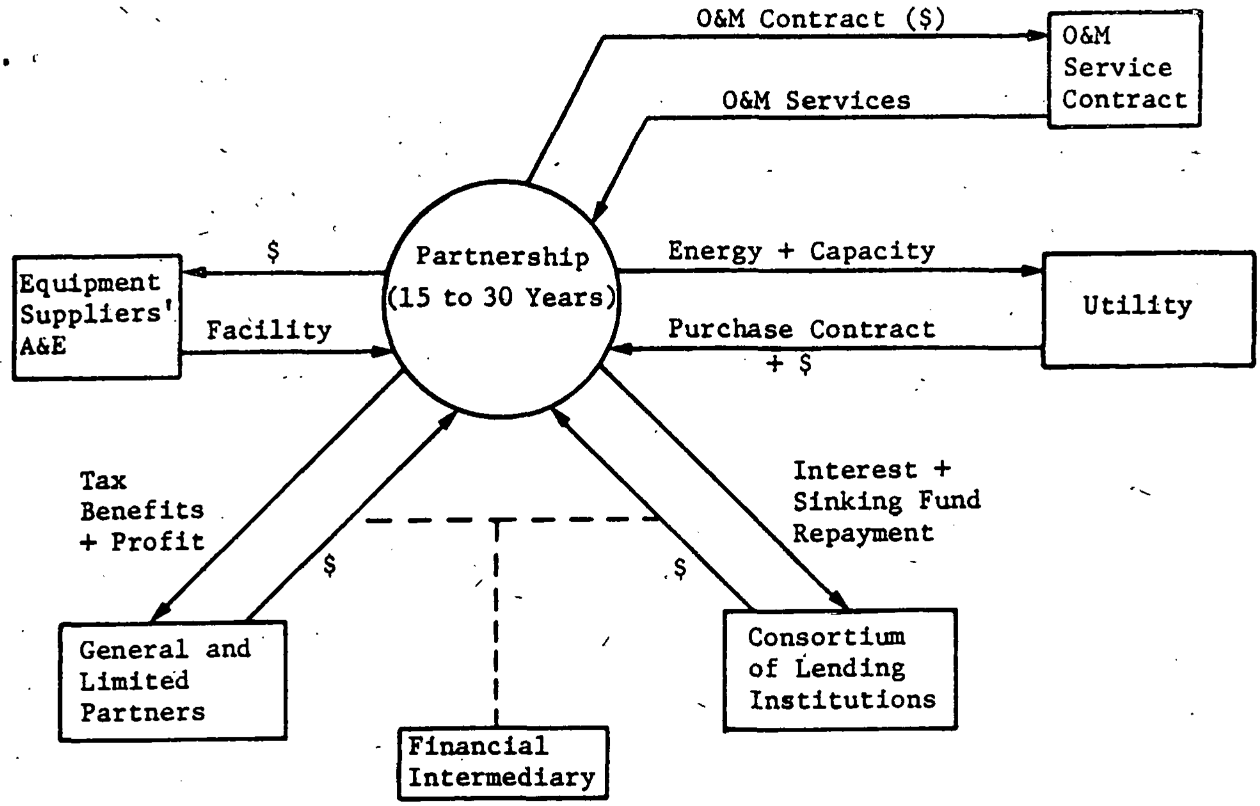

Figure IV-2 General Structure of Partnership

Another key issue is the tax environment of the project. The structuring of the partnership and contracts between the participants could affect the tax treatment of the project. With the assumed debt/equity structure, the loss of the energy tax credit seriously erodes the return on equity.

With the project financing approach, there is considerable latitude to counteract negative changes in the economic and legislative environment. For example, more favorable interest rates can markedly improve return on investment. An approach currently being investigated, using the structure presented earlier, is to increase the debt fraction to 90 to 100%. This requires initial indirect credit support by a large investor, but the return should be commensurate with risk.

Project financing, typically used in the oil and gas industry, is a good approach to financing large PV plants. The project financing approach provides the third parties with a large tax shelter in the early years of the project and an inflation-proof revenue stream for a long period (30 years), with no deterioration in balance sheet or credit position.

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