Fourth Photovoltaic Systems Definition and Applications Projects Integration Meeting Albuquerque, New Mexico April 12, 13, 14, 1983

Gary Jones

Prepared by Sandia National Laboratories Albuquerque, New Mexico 87185 and Livermore, California 94550 for the United States Department of Energy under Contract DE-AC04-76DP00789

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ABSTRACT

This report is a compilation of the abstracts and visual material used in presentation at the Fourth Photovoltaic Systems Definition and Applications Projects Integration Meeting held at the Marriott Hotel, April 12-14, 1983, in Albuquerque, New Mexico. The meeting, sponsored by Sandia National Laboratories and the United States Department of Energy, provided a forum for detailed analyses on recently completed and current activities. These activities include systems research, balance-of-system technology development, residential experimentation, and evaluation of intermediate-sized applications.
FOURTH PROJECT INTEGRATION MEETING
OF THE
SANDIA PHOTOVOLTAIC SYSTEMS DEFINITION AND APPLICATION EXPERIMENT PROJECTS

Meeting Objectives

This is the Fourth Project Integration Meeting for the Sandia Photovoltaic Systems Definition and Application Experiment Projects. The focus is on the current major issues facing photovoltaic systems and subsystems:

- utility interfacing and integrating
- array field design
- power conditioning performance
- operation and maintenance requirements

The meeting objectives are to

- Review the current understanding of photovoltaics system design and development, assisting in the transfer of this technology to industry.
- Exchange information on on-going work and system-related activities.
- Provide a means of coordinating project and program activities.

This meeting will emphasize the experience gained in the intermediate application experiments, the current residential systems research activities, and progress in technology transfer.
# AGENDA

## FOURTH PHOTOVOLTAIC SYSTEMS INTEGRATION MEETING

**APRIL 12, 13, 14, 1983**

### TUESDAY, APRIL 12

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<td>8:30</td>
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<td>8:40</td>
<td>THE PV PROGRAM STATUS AND ACTIVITIES</td>
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<td></td>
<td>E.S. DAVIS, JPL</td>
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<tr>
<td>9:00</td>
<td>SYSTEMS RESEARCH OVERVIEW</td>
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<td>G.J. JONES, SNLA</td>
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<tr>
<td>9:30</td>
<td>RESIDENTIAL DOCUMENTATION</td>
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<td>M.G. THOMAS, SNLA</td>
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<td>10:00</td>
<td>BREAK</td>
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<tr>
<td>10:30</td>
<td>INSTANTANEOUS RESIDENTIAL LOADS - WHY?</td>
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<td>G. COLLAROS, BDM</td>
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<td>11:00</td>
<td>PHOTOVOLTAIC RELIABILITY MODEL</td>
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<td>L. STEMBER, BATTELLE COLUMBUS</td>
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<td>11:30</td>
<td>PV AND UTILITY CONTROL</td>
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<td>A. BOSE, ARIZONA STATE UNIVERSITY</td>
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<td>12:00 - 1:30</td>
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TUESDAY, APRIL 12

SESSION II  ARRAY FIELD ENGINEERING AND SUBSYSTEM RESEARCH

CHAIRMAN: H.N. POST, SNLA

1:30 SESSION INTRODUCTION
H.N. POST, SNLA

1:40 MODULAR ARRAY FIELD INSTALLATION
D.C. CARMICHAEL, BATTELLE-COLUMBUS LABORATORIES

2:20 MODULAR ARRAY FIELD INSTALLATION
G.J. NAFF, HUGHES AIRCRAFT CO.

3:00 BREAK

3:30 SYSTEM GROUNDING AND FAULT PROTECTION
W.J. STOLTE, BECHTEL GROUP

4:00 AUTOMATED INSTALLATION
J.R. OSTER, JR., BURT HILL KOSAR RITTELMANN ASSOC.

4:25 MODULAR DESIGNS FOR LARGE ARRAY FIELDS
D. CARMICHAEL, BATTELLE-COLUMBUS, LABS.

4:50 SUMMARY AND WRAP-UP

5:00 - 7:00 SOCIAL HOUR, NO HOST BAR

WEDNESDAY, APRIL 13

SESSION III  PCS HARDWARE DEVELOPMENT

(ISSUES: COST AND PERFORMANCE)
### SESSION III (CON’T)

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<tr>
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<td>SESSION INTRODUCTION</td>
<td>T. Key, SNLA</td>
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<td>200 Vdc/4kW, 20 KHz UTILITY INTERFACE PCS</td>
<td>S. Cuk, TESLACO</td>
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<td>200 Vdc/4kW, 20 KHz UTILITY INTERFACE PCS</td>
<td>R. Steigerwald, General Electric</td>
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<tr>
<td>9:20</td>
<td>48 Vdc/3kW, 100 KHz UTILITY INTERFACE PCS</td>
<td>J. Ross, Alpha Energy Systems</td>
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<tr>
<td>9:40</td>
<td>60kW, 3Ø SCR/GTO HYBRID PCS</td>
<td>W. Rippe, JPL</td>
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<td><strong>BREAK</strong></td>
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<td>10:30</td>
<td>PCS PERFORMANCE TESTING</td>
<td>T. Key and W. Bower, SNLA</td>
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<td>UTILITY/PCS INTERFACE STUDIES</td>
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<td></td>
<td>(ISSUES: HARMONICS AND CONTROL)</td>
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<td>11:00</td>
<td>ACTIVITY SUMMARY</td>
<td>J. Stevens, SNLA</td>
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<td>11:10</td>
<td>INTERPRETATION OF DYNAMIC SIMULATION RESULTS</td>
<td>O. Wasynczuk, Purdue University</td>
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<td>11:35</td>
<td>EFFECT OF PV INVERTERS ON DISTRIBUTED FEEDERS</td>
<td>J. Fitzer, University of Texas at Arlington</td>
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<td>PCS PERFORMANCE TESTING</td>
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<td>UTILITY/PCS INTERFACE STUDIES (ISSUES: HARMONICS AND CONTROL)</td>
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CHAIRMAN: T. HARRISON, SNLA

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<td>OPERATIONAL EXPERIENCE AT LOVINGTON AND NEWMAN</td>
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<td>OPERATIONAL EXPERIENCE AT OCSA</td>
<td>D. SORENSON, SAI</td>
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9:20    NE RES - RESULTS AND ISSUES
        E. KERN, MIT/EL

9:50    BREAK

10:10   SW RES - RESULTS AND ISSUES
        J. SCHAEFER, NMSEI

10:40   HAWAIIAN PV RESIDENCES
        G. CURTIS, HNEI

11:00   TECHNIQUES FOR HANDLING MISSING RESIDENTIAL DATA
        D. MENICUCCI, SNLA

11:20   UTILITY INTERESTS IN RESIDENTIAL PV
        S. FIRSTMAN, GEORGIA TECH

11:40   RESIDENTIAL PV INSTALLATION COSTING
        D. PENASA, UHL AND LOPEZ

12:00   ADJOURN
PROJECT STRUCTURE OF THE SANDIA PHOTOVOLTAIC ACTIVITIES

PHOTOVOLTAIC PROJECTS
PROJECT MANAGER
E. L. BURGESS

PROJECT INTEGRATION TASK

SYSTEMS DEFINITION PROJECT
G. J. JONES

ARRAY SUBSYSTEMS RESEARCH TASK
H. N. POST

SYSTEMS RESEARCH TASK
G. J. JONES

POWER CONDITIONING RESEARCH TASK
T. S. KEY

SOLAR CELL RESEARCH TASK
D. ARVIZU

MODULE RESEARCH TASK
M. W. EDENBURN

ARRAY RESEARCH TASK
A. B. MAISH

INTERMEDIATE EXPERIMENTS TASK
T. D. HARRISON

SYSTEM APPLICATIONS PROJECT
E. L. BURGESS

RESIDENTIAL EXPERIMENTS
K. BIRINGER

SYSTEM & COMPONENT TEST PROJECT
J. F. BANAS

ADVANCED SYSTEMS TEST FACILITY TASK
H. J. GERWIN
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SANDIA PHOTOVOLTAIC PROJECTS (Continued)

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**System Applications Project**

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**Other**

DOE/ALO Energy Technologies Division

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SESSION I

Session Chairman: Gary Jones
THE PV PROGRAM STATUS AND ACTIVITIES

E. S. DAVIS

JPL
Photovoltaic Systems and Applications
Project Integration Meeting

SYSTEMS DEVELOPMENT AND
APPLICATIONS, AN OVERVIEW

by
E.S. (Ab) Davis

April 12, 13, 14, 1983
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Federal Photovoltaic Utilization Program
INTRODUCTION

Scope:
Application endeavors not included in the
Sandia Program

• Individuals
• Private Corporations
• EPRI and utilities
• U.S. government agencies
• Foreign companies and governments

THE ARCO Solar ONE-MW
PHOTOVOLTAIC POWER PLANT
NEAR HESPERIA, CALIF

TWO-AXIS TRACKING STRUCTURES
AT THE ARCO Solar POWER PLANT
POWER CONDITIONING FOR THE ARCO POWER PLANT
ONE 1000 kVA GARRETT AND TWO 500 kVA HELIONICS INVERTERS

SMUD SITE

Federal Photovoltaic Utilization Program
COMPARISON OF ARCO LUGO & SMUD PV-1

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<th>SMUD PV-1</th>
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<tr>
<td>Concept</td>
<td>2-axis tracking</td>
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<td>Dc peak power</td>
<td>1.0 MW</td>
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<td>Power array</td>
<td>9.5 kW</td>
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<td>Modules array</td>
<td>256</td>
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<tr>
<td>Ground coverage</td>
<td>13-15%</td>
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<tr>
<td>Power conditioning units</td>
<td>2 @ 1 MW</td>
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EPRI’s program in photovoltaic systems
• Integrated photovoltaic central station conceptual designs. (Black & Veatch, Kansas City)
• High concentration PV array development (Black & Veatch, Kansas City)
• Photovoltaic field-test performance assessment (Boeing Co. Computer Service (Interim Report Aug 8))
UTILITIES INVOLVED IN PHOTOVOLTAICS

INTEGRATION AND ASSESSMENT STUDIES
- Public Service Electric and Gas Co. Newark, New Jersey

SYSTEM DESIGN AND EVALUATION
- Arizona Public Service Co. Phoenix, Arizona

COMPONENT DEVELOPMENT AND TESTING
- Arizona Public Service Co.

Ref: EPRI electric utility solar energy activities 1982 survey update.

FIELD TEST AND DEMONSTRATIONS (Cont'd)
- Arizona Public Service Co.
- Florida Power & Light Co.
- Philadelphia Electric Company (2)
- Portland General Electric Co.
- Public Service Co. of Indiana
- San Diego Gas and Electric Co.
- Southern California Edison Co. (2)

MONITORING
- Public Service Company of New Mexico

A 4.4 kW RETROFITTED RESIDENTIAL PHOTOVOLTAIC SYSTEM
ARIZONA PUBLIC SERVICE CO.

GEOGRAPHIC DISTRIBUTION OF UTILITIES INVOLVED IN PHOTOVOLTAICS

Ref: EPRI electric utility solar energy activities 1982 survey update
Federal Photovoltaic Utilization Program

U.S. GOVERNMENT AGENCIES

- Brookhaven National Laboratory
- NASA Lewis Research Center
- Oak Ridge National Laboratory
- Federal Photovoltaic Utilization Program

Federal Photovoltaic Utilization Program

U.S. GOVERNMENT AGENCIES (Cont'd)

NASA - Lewis Research Center
Purpose is to increase the technology base for PV stand-alone systems
- PV - Hybrid Systems
- Combined Modular System BOS Cost Sensitivity Study (Hughes)

Oak Ridge National Laboratory
Provides technical assistance to DOE in evaluating work performed under several PV demonstration project grants
- Georgetown University
- Mississippi County Community College
- Northwest Mississippi Junior College

Federal Photovoltaic Utilization Program

U.S. GOVERNMENT AGENCIES (Cont'd)

APPLICATIONS: NUMBER PER AGENCY

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<td>Department of Defense</td>
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<td>Environment Protection Agency</td>
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TOTAL: 1,180

*TOTAL NUMBER DOES NOT INCLUDE 1,800 USGS NAVDAP APPLICATONES*

Federal Photovoltaic Utilization Program

U.S. GOVERNMENT AGENCIES (Cont'd)

Largest System Installed
Air Force Post Exchange at McClellan AFB, California
36 kWp

Largest System Planned at the Naval Weapons Center
2 - 25 kWp

Smallest System
Meteorological Data Buoy, NOAA
0.01 kWp

Largest Portable
Trailer mounted pumping system
0.88 kWp
Federal Photovoltaic Utilization Program

U.S. GOVERNMENT AGENCIES (Cont’d)

- Smallest Portable
  EPA backpack 0.04 kWp

- System subjected to the worst environmental conditions
  Navigational lights and buoys

- Systems satisfying the greatest human needs
  Comfort Stations

FOREIGN COMPANIES & GOVERNMENTS (Cont’d)

Canada
Michron Energy Ltd., Ottawa
Integrates PV with diesel

Great Britain
BP Solar Systems, Haddenham
30 kWp PV system to start in June 83

Germany
AEG - Telefunken, West Germany
40 - 10,000 W solar power pack

Mexico and West Germany Consortium
Solar Reverse Osmosis (SORO) 2.3 kWp array

Ireland
Sponsored by European Economic Commission
50 kWp system for a commercial dairy

FOREIGN COMPANIES AND GOVERNMENTS

Japan
Sunshine Project includes about 20 organizations including universities, industry and the New Energy Development Organization

- Single
- Multiple
- Utility

Saudia Arabia
Soleras

SOLERAS
The System Research Task is responsible for developing the photovoltaic technology base in the area of system design and subsystem performance requirements. In the past, this has focused on the development of detailed designs. These designs were then analyzed and cost-drivers identified. Where possible the optimum or lowest life-cycle cost subsystem options were determined and designs updated to reflect this. This is somewhat of an iterative process since field test data is necessary to validate results.

The initial phase of this work has now been completed for all sectors. Therefore the current emphasis in systems research is the verification of this previous work, by analysis of the original assumptions in light of recent data. This is followed by the documentation of this information in a form suitable for the potential user. The residential sector status is being summarized in documents that are in preparation. The verification phase is just starting for the other sectors.
SYSTEM RESEARCH OVERVIEW

GARY J. JONES

APRIL 12, 1983
THE ROLE OF PHOTOVOLTAIC SYSTEM RESEARCH

TO AID IN THE DEVELOPMENT OF EFFECTIVE PHOTOVOLTAIC SYSTEMS BY

1. CONTRIBUTING TO THE UNDERSTANDING OF:
   
   • PHOTOVOLTAIC SYSTEM OPERATION
   
   • THE OPERATING ENVIRONMENT
   
   • SUBSYSTEM REQUIREMENTS AND SELECTION

2. TRANSFER THIS UNDERSTANDING TO THE POTENTIAL USER
SYSTEM DESIGNS WAS THE FIRST STEP

HAVE COMPLETED:

- EXAMPLE DESIGNS FOR ALL SECTORS
- A RELIABILITY ANALYSIS MODEL
- DATA REQUIREMENTS FOR PERFORMANCE VERIFICATION

BUT:

- NO DESIGN FOR TRACKING FLAT PANEL FIELD
- UNCERTAINTY IN FIELD DESIGN/OPERATING CHARACTERISTICS FOR LARGE FIELDS
- RESIDENTIAL DESIGNS DO NOT INCORPORATE OPTIMAL MOUNTING CONCEPT (NOT IDENTIFIED)
- PERFORMANCE PREDICTION IS QUESTIONABLE
SYSTEM DESIGN: WHAT'S NEXT?

- CONTINUED INVESTIGATION OF DESIGN SENSITIVITY
- A DESIGN FOR TRACKING FLAT PANEL FIELDS
- IMPACT OF ADVANCED TECHNOLOGIES
THE UTILITY IS THE OPERATING ENVIRONMENT

HAVE COMPLETED:

- Future energy supply impacts on avoided cost
- The role of energy storage and on-site loads
- Initial look at capacity credit

BUT:

- Have not characterized impact of stochastic source
- No data on PV effects on T&D design
- Time-dependent value of energy not analyzed
FUTURE UTILITY/PV ANALYSIS PLANS

- TRANSMISSION/DISTRIBUTION IMPACTS

- COMPLETION OF ONGOING STOCHASTIC EFFECTS STUDY

- ASSESSMENT OF POSSIBLE DYNAMIC IMPACTS

- EXTENSION OF EXISTING RESULTS TO TIME-VALUE ASPECTS
SUBSYSTEM TRADEOFF ANALYSIS IS KEY TO TECHNOLOGY DEVELOPMENT

HAVE COMPLETED:

- TRADEOFF ANALYSIS FOR LARGE SYSTEMS
- EFFICIENCY/COST REQUIREMENTS FOR MODULES
- INITIAL ANALYSIS OF TRACKING FLAT PANELS
- COST ANALYSIS OF RESIDENTIAL ARRAY MOUNTING

BUT:

- RECENT BATTELLE RESULTS QUESTION HIGH-VOLTAGE ASSUMPTIONS
- DEFINITIVE TRACKING STATEMENT REQUIRES VERIFICATION OF INSOLATION/HARDWARE ASSUMPTIONS
- OPTIMUM THERMAL/ECONOMIC RESIDENTIAL ARRAY APPROACH IS NOT IDENTIFIED
- DEGRADATION/RELIABILITY FIELD DATA LACKING
SUBSYSTEM REQUIREMENT DEFINITION PLANS

- REASSESS LARGE SYSTEM ARRAY FIELD TRADEOFFS
- INVESTIGATE "NEW" RESIDENTIAL ARRAY APPROACHES
- MONITOR NEW INSOLATION DATE AND PLANNED ARRAY DESIGN STUDIES
TECHNOLOGY TRANSFER NEEDED
TO ASSURE RESEARCH VALUE

HAVE COMPLETED:

- A DESIGN HANDBOOK FOR GRID CONNECTED APPLICATIONS
- CODES FOR SYSTEM DESIGN COMPATIBLE WITH HOME COMPUTERS

BUT:

- NO DEFINITIVE DOCUMENT SUITABLE FOR USE BY A/E COMMUNITY FOR ANY SECTOR
- PROGRAM REPORTS REALLY AIMED AT RESEARCH COMMUNITY
AN APPROACH TO MORE EFFECTIVE TECHNOLOGY TRANSFER

- COMPLETE THE RESIDENTIAL DOCUMENTATION EFFORT NOW UNDERWAY

- INITIATE PARALLEL EFFORTS FOR INTERMEDIATE AND CPS APPLICATIONS
THE FUTURE EMPHASIS IS ON DEFINITIVE STATEMENTS

THE APPROACH OF SYSTEMS RESEARCH IN THE FUTURE WILL BE TO

- REASSESS OLD ASSUMPTIONS
- FOCUS WHERE NEW RESULTS CONTRAST WITH OLD ASSUMPTIONS
- UPDATE DESIGN GUIDANCE AND SUBSYSTEM REQUIREMENTS AS NECESSARY
- DOCUMENT THIS INFORMATION IN FORM MOST SUITABLE FOR DISTRIBUTION
The PV Residential Documentation Effort

Mike Thomas

Extended Abstract

The Residential Documentation effort is a comprehensive compilation of residential PV systems information. Currently no other effort has attempted to provide a complete description of any PV technology for an entire application sector. This omission impedes technology transfer.

The data base for this project is the many hundreds of documents that have been prepared during the National Photovoltaic Program. Fourteen topical reports, 30-50 pages each, are being written to cover all aspects of residential PV system design issues. These reports constitute an intermediate level of documentation which presents the state-of-the-art analytically, and whose primary audience is the A&E. An overall summary will also be prepared and will serve as an overview for a broader audience and as access to the other documents in the series. Although the primary objective is to provide an analysis of residential PV systems, it also serves to identify deficiencies in the data base.

A team of scientists, engineers, architects, and economists have been assembled to assure a non-parochial treatment in the effort. Under the leadership of SNLA personnel, the team includes individuals from the American Institute of Architects, General Electric, Solar Energy Research Institute, and the Jet Propulsion Laboratory. In addition, an extensive review process has been established and includes peer review by the participants, and outside review by eight A&E firms, DOE and EPRI.

The information in the documents is divided into five areas:

- Background and Rationale
- Alternate-Designs Considerations
- The Design Process
- Completing the Job
- Where to Find More Information

The background and rationale includes a description of the basic PV concept, PV cells, preliminary assessments and methods, and other concerns regarding PV. The alternate-design considerations discuss certain areas of limited application. The design process area covers the array, PCS, tradeoffs, and tools to aid in the design. These discussions are supplemented by a discussion on installation and operation and by a comprehensive bibliography.

Drafts of each of the topical reports were completed during the winter quarter with an anticipated publication date for the collection of October 1983.
THE PV RESIDENTIAL SYSTEMS DOCUMENTATION EFFORT

PV SYSTEMS DEFINITION PROJECT

SANDIA NATIONAL LABORATORIES
THE DOCUMENTATION EFFORT: A COMPILATION
OF RESIDENTIAL SYSTEMS INFORMATION

Two levels of documentation have been added to the technology base:

- Executive summary
- Topical reports
- Hundreds of reports on residential PV
THE OBJECTIVES SHOULD LEAD TO USE IN
THE PRIVATE SECTOR

• Document state-of-the-art analyses
• Identify deficiencies in the data base
• Provide a vehicle for technology transfer
THE INTENDED AUDIENCE COVERS

A BROAD RANGE

Decision Makers

Application
architects and engineers

Assessment

Research and Development

Technology Base
THE DOCUMENTATION IS A TEAM EFFORT

organizations involved in writing
SERI, JPL, SNLA, GE, AIA

organizations involved in review
8 A & E firms, EPRI, DOE and participants

background of participants
architects, engineers, scientists, economists, etc.
THE MAJOR PURPOSE OF THE DOCUMENTS IS TO INFORM

Executive Summary

- Photovoltaics is a simple electrical source
- Characteristics include initial capital cost with low operational cost
- Realistic assessment - pros and cons
- Stand-alone, use level 2 for expanded discussion
BACKGROUND AND RATIONALE

1. The basics - what is PV, what materials, & why modules

2. Preliminary Assessment - how does PV fit & am I interested

3. Institutional Environment - issues involved

4. Economics - why would I bother, simple and complex methods

5. Utility - what am I competing with
ALTERNATE-DESIGN CONSIDERATIONS

6 PV/T Flat Plate Collectors - mismatch between thermal & PV, tradeoff between savings for combination and efficiency loss

7 Storage and DC Loads - storage decoupled from PV value for grid connected DC loads will not replace AC

8 Application to the Existing Home - the special design considerations with a fixed structure
THE DESIGN PROCESS

9 Array Subsystem - methods of configuring modules and wiring, safety aspects, and array/PCS interaction

10 Power conditioning Subsystem - needs for utility interactive power conditioner power quality and utility-PV protection

11 Design and Tradeoffs - optimization of design by comparative analyses

12 design Tools - available tools and use
COMPLETING THE JOB

13 Installation and Operation - the safety and operational considerations for implementation

WHERE TO FIND OUT MORE ABOUT IT

14 Comprehensive Bibliography - access to level 3 documentation
TIMETABLE TARGETS FY83 COMPLETION

Winter Quarter 83 - drafts of level 2 documents

Spring Quarter 83 - internal review, revisions

Summer Quarter 83 - external review, publication completion of Executive Summary draft
The Detailed Residential Electric Load Determination Program was initiated to measure residential electric loads at instantaneous intervals and determine the effects of using instantaneous load data in annual residential photovoltaic (PV) power systems performance simulations. The fundamental objectives of this program were to measure real, instantaneous load data, and develop a statistical model based on this measured data to predict residential electric demand. Residential load data are currently being collected at 15-minute intervals by utilities throughout the nation. With this large data base the statistical model can be used to predict the instantaneous load demand for PV systems in any area of the country. For performance predictions the statistical model was incorporated into SOLCEL, a Sandia National Laboratories-developed computer simulation code designed specifically for the analysis of PV systems.

Residential electric load patterns were directly measured at 5-second intervals on four residences selected in the northeast, southeast, and southwest regions of the country. The data acquisition hardware configuration is shown in Figure 1. A load data base consisting of 5,080 complete, continuous, 15-minute intervals, was established (53 days). Load data were collected for a 2-week period during the summer and again in the winter.

A major finding of this program was the limited occurrence of active load profiles. An active profile exhibits a high energy level above the 15-minute average, high squared multiple correlation which means the model adequately explains variability, and usually occurs between 5:30 am and midnight. Inactive profiles, in contrast, are steady state loads which closely follow the 15-minute time-average data and occur mostly during the night, mid-morning, and afternoon. Sample active and inactive profiles are shown in Figures 2a and 2b.

After the load data were statistically characterized (Figure 3), only 734 intervals, out of the 5,080 intervals in the data base, possessed the characteristics described above which statistically identified them as an active profile and differentiated them from the 15-minute time-average load. This limited occurrence of active profiles substantially reduced the probability that an active profile would occur when the statistical model was exercised, and annual system performance simulations conducted.

Annual performance was simulated on a 4-Kw residential array using 1 year of real load data at a 15-minute interval and a year of solar radiation and weather data for Albuquerque, New Mexico. The simulation was performed using 1-hour interval data, 15-minute interval data, 15-minute interval data with the instantaneous load model, and 15-minute interval data with the instantaneous load model but with double the probability of an active profile occurring. The performance comparisons are shown in Figure 4. Using hourly load data the array supplies 38 percent of the annual load. The use of 15-minute load data produces a decline of 1.4 percent in the fraction of the load met by the array. The use of the instantaneous model however produces a decline of less than 1 percent from the PV fraction calculated by the use of 15-minute data. The model using twice the probability of an active profile produces a decline in the PV fraction by 1.4 percent.

The conclusion which could be drawn from these performance comparisons indicates that 15-minute load data are adequate for small residential PV system simulations. Firm conclusions however would be inappropriate at this time. Further SOLCEL simulations are being conducted to examine the sensitivity of performance predictions to variations in the PV array size, probability of an active instantaneous load, seasonal weather, climate, and daily weather effects. These results (Figures 5 and 6) will be presented at the Systems Integration Meeting. The small number of active load profiles which were identified in the data base however would indicate that the occurrence and effect of instantaneous data is less significant than had been previously believed.
Figure 1. DRL Data Acquisition Hardware Configuration
Figure 2a. Sample Instantaneous Load Profiles
Figure 2b: Sample Instantaneous Load Profiles (Concluded)
Figure 3. Modeling Methodology
### ANNUAL PERCENT LOAD SUPPLIED

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**Figure 4.** Results from SOLCEL Simulations
DETERMINATION OF THE SENSITIVITY OF PV SYSTEM PERFORMANCE TO:

1) VARIATIONS IN THE PROBABILITY OF AN ACTIVE INSTANTANEOUS LOAD PROFILE

2) VARIATIONS IN PV ARRAY SIZE

3) SEASONS

4) CLIMATE

FIGURE 5. DETERMINATION OF SENSITIVITY

RESULTS

1) 3-D SURFACE OF PV ARRAY SIZE, PROBABILITY OF ACTIVE PROFILE VS. PV ARRAY EFFICIENCY - DISPLAYED AS PV ARRAY EFFICIENCY (PERCENTAGE OF PV ARRAY OUTPUT WHICH GOES TOWARD THE LOAD) CONTOURS ON GRAPHS OF PV ARRAY SIZE VS. PROBABILITY OF ACTIVE PROFILE

2) PLOTS CONSTRUCTED FOR EACH MONTH AND YEAR AVERAGE

FIGURE 6. RESULTS
ABSTRACT

RELIABILITY, AVAILABILITY AND MAINTENANCE-COSTS MODELS FOR USE IN THE DESIGN OF PHOTOVOLTAIC POWER SYSTEMS

L. H. Stember

Battelle's Columbus Laboratories
505 King Avenue, Columbus, Ohio 43201

Two techniques were developed under Contract 62-8278 for modeling the availability and maintenance costs of photovoltaic power systems. The models use system-specific input data on system design, subsystem reliability, and maintenance time and costs.

The starting point for the application of these modeling techniques is the specific PV system design. Such modeling is normally based on fully working components and cells, without accounting for the effects of failure and degradation over time. However, in these models, the design information is combined with reliability data, and corrective and preventive maintenance data. Also, data on power output degradation from dirt on the array, permanent damage to the array surfaces and individual cell failures are used.

The availability model requires that a design simulation of the array energy production be conducted on a monthly basis using site-specific data. This is a normal part of the PV system design process. The model also makes use of the output from a technique such as JPL's "Flat Plate PV Module and Array Circuit Design Optimization Methodology", which predicts array output power degradation over time caused by cell failures. In this way the effects of series-parallel cell design and bypass diodes are incorporated.

The reports on this study contain detailed descriptions of the development of the techniques and their application to four PV systems (Sandia Reports No. SAND82-7126/1, -7126/2, and -7152). Two basic availability models were developed to the operational stage. These are: (1) the simulation technique using the GASP IV language, and (2) the analytical approach using state-space techniques. The simulation model developed is called "SOLREL". It uses event-by-event simulation to represent the 30-year life of the system with individual reliability and maintenance events modeled with statistical distributions. The state-space technique uses an exponential form for both failure and repair-time distributions. It is thus able to make use of Markov chain solutions to the system-specific mathematical models. Both approaches predict annual energy produced and annual maintenance costs.

The predicted annual energy produced, resulting from analyses which consider lifetime-related failure and degradation factors, provides more useful information as an input to life-cycle energy cost calculations than a no-failure estimate. In addition, the annual maintenance costs resulting from both corrective maintenance and preventive maintenance activities are computed. This predicted maintenance cost factor provides previously unavailable information; and, with good data input, allows a realistic forecast of the life-cycle energy cost.

By changing the design and maintenance strategies, and then re-analyzing the system using these models, it is possible to evaluate the effect of changes on life-cycle energy costs. As an example, this approach was used for "time between cleanings". As this time interval is increased, the cost per kilowatt hour goes down because the decrease in maintenance cost is not offset by the decrease in power produced. However, once a 12-month interval is reached, this situation turns around and it is more effective to clean rather than allow the array power to degrade further. Other parameters may be varied, in an analogous way or the effect of different specification values for reliability, efficiency, or maintenance time may be judged. In this way these methodologies can be used in making design decisions from the long-range viewpoint with a goal toward minimizing life-cycle energy costs. The results can be used in procurement specifications and guidelines for purchasing the subsystems.
PROGRAM OBJECTIVES

- DEVELOP SYSTEM RELIABILITY/MAINTAINABILITY METHODOLOGY FOR PV POWER SYSTEMS

- INCLUDE SUBSYSTEM DEGRADATION EFFECTS IN THE METHODOLOGY

- ESTIMATE SUBSYSTEM RELIABILITY AND REPAIR PARAMETERS

- INTEGRATE THE OUTPUT OF THE METHODOLOGY WITH LIFE-CYCLE COST MODELS
OVERVIEW OF INTERACTIONS OF AVAILABILITY METHODOLOGY WITH THE SYSTEM DESIGN PROCESS

- **Load Requirements**
- **PV System Design Process Including JPL Array Analysis and SOLTRM Simulation**
  - Power Output Duration Curves
  - Monthly Availability Model (SOLREL)
  - Initial System Cost and Annual Operating Cost
  - List of All Failure/Repair Events Over Life
  - Annual Energy Output
  - Annual Maintenance Cost
  - Life-Cycle Energy Cost Model

- **Cell-Component-Subsystem Reliability and Degradation Data**
- **Equipment/Subsystem Maintenance Policy, Repair Times, and Costs**
- **Financial Parameters—Discount Rate, Inflation, etc.**

**MONTHLY INSOLATION FOR LOCATION**

**INCREMENT DESIGN AND COMPARE FOR MINIMUM LIFE-CYCLE ENERGY COST**

**C/kWh**

Battelle
Columbus Laboratories
CHANGES IN ARRAY POWER OUTPUT OVER TIME AS RESULT OF CELL FAILURE — M.I.T. RESIDENTIAL FLAT-PANEL SYSTEM

MIT-LL RESIDENTIAL SYSTEM (6.8 Kw) DEGRADATION FOR SPECIFIED CELL FAILURE RATES (CFR)
POWER OUTPUT DURATION CURVE — FOR 1 OF 12 MONTHS OF TYPICAL YEAR

OUTPUT DURATION CURVE

e.g., Sixty hours per month, array power output \( \geq 300 \text{ kW} \)

OUTPUT IN KW

MAX

300

HOURS/MONTH

60

280

Battelle
Columbus Laboratories
SUBROUTINE: INCREMENTAL ENERGY COMPUTATION

INPUT FOR EVENT "N"

- POWER OUTPUT DURATION CURVE
- INVERTER LOSSES
- PWR. LOST – DIRT (RECOVERABLE)
- PWR. LOST – PERMANENT DEGRADATION OF MODULES
- TIME SINCE EVENT (N-1)

COMPUTATION

USE TIME-RELATED DEGRADATION AND COMPUTE ENERGY GENERATED SINCE EVENT (N-1)

OUTPUT

\[ \Delta E \text{ [(N-1) TO N]} \]
FLOWCHART OF SIMULATION

INPUT

- M_c HR & MATL COST
- SUBSYSTEM FAILURE DISTRIBUTIONS
- SUBSYSTEM M_c AND M_p LABOR-TIME DISTRIBUTIONS
- PREVENTIVE MAINTENANCE AND CLEANING SCHEDULE
- CALENDAR AND SYSTEM LIFE GOAL
- M_p HR & MATL COST

COMPUTING

- CONSTRUCT EVENT FILE
- TIME/EVENT SIMULATION OF PV SYSTEM
- SUBROUTINE - INCREDMENTAL ENERGY COMPUTATION
- LABOR & MATL COST FOR CORRECTIVE MAINTENANCE
- LABOR & MATL COST FOR PREVENTIVE MAINTENANCE AND CLEANING

OUTPUT

- M_c COSTS
- M_p COSTS
- ENERGY PRODUCED
- M_p COSTS

MONTHLY CUMULATIVE

SPECIAL REPORTS
RESULTS OF APS ANALYSIS, CURRENT VALUE, ANNUAL MAINTENANCE COST AND ENERGY PRODUCED

COST BY YEAR
SYSTE OUTPUT BY YEAR

Battelle Columbus Laboratories
Abstract

ANALYSIS OF THE STOCHASTIC PROPERTIES OF PHOTOVOLTAIC ELECTRIC GENERATION ON THE OPERATION OF UTILITY SYSTEMS

P.M. Anderson Anjan Bose P.E. Russell
Arizona State University

The electric power systems of North America consist of very large interconnected regions where large electrical load centers are interconnected with large power plants by a network of high voltage transmission lines. These regions are supplied by rotating synchronous generators that operate at speeds corresponding to a multiple of 60 Hz, the system frequency. The system dynamics are quite stable, largely because of the enormous moment of inertia of these large rotating turbine generator systems. This helps maintain the supply frequency at a nearly constant value. This frequency is monitored by a system control center, which has communication with the generating plants and is capable of dispatching changes in generators to maintain nearly constant frequency at optimum operating cost.

New generating technologies, such as photovoltaic power plants, have greatly different characteristics from the conventional boiler-turbine-generator systems. These new generating concepts are inertialess systems, capable of much faster response rates. This means that they can provide fast control, but will not contribute inherently to frequency stability. Thus, it is conceivable that there may be an upper limit to the desirable penetration level of these advanced plants, at least under the present operating and control concept. Moreover, a photovoltaic power plant has no energy storage, such as the large thermal storage of a conventional plant. This means that rapid generation changes due to clouds must be compensated for by the storage capacity, and perhaps by the dispatch schedule, of conventional thermal plants.

The purpose of this project is to investigate the stochastic behavior of photovoltaic power plants when integrated into a utility system, with the specific objective of studying the effect on utility operation, control, and generation dispatch. These concepts will be studied by special purpose computer dynamic simulations that have the capability of representing the power plants, the loads, and the system control center actions. These simulations demonstrate the effect on system control of rapid PV generation changes under any desired operating condition. In this way it is possible to judge the effectiveness of system control, as measured by industry given standards, in the operating environment that includes large amounts of PV generation.

One of the essential tasks in this project is the development of a PV system model that includes the effect of cloud behavior. This is done in two ways: first by a deterministic model of clouds passing over an array at constant velocity, and finally by a stochastic cloud pattern that tends to rapidly vary the PV output with time. Both these ramp effects and random effects are important considerations in the overall system control. Simulation of power system operation with and without such PV performance should provide valuable new insights as to the nature of this new technology impact.

The system loads to be considered are taken from a family of typical utility systems published by EPRI. Using this load set collection, a wide variety of system conditions may be considered, from fast load increase to fast decrease, as well as rapid peaking or dipping tendencies. These load conditions provide a wide range of conditions that might be experienced by a utility. Varying this load condition, as well as the generation mix, provides a flexible evaluation tool for analyzing the stochastic behavior of PV generation under cloudy conditions.
ANALYSIS OF THE STOCHASTIC PROPERTIES
OF PHOTOVOLTAIC ELECTRIC GENERATION ON THE
OPERATION OF UTILITY SYSTEMS

Purpose: The purpose of this project is to study certain stochastic properties of photovoltaic systems when integrated into utility generation and transmission systems, with the specific objective of studying the effect on utility operation, control, and generation dispatch.

SCOPE: The scope of the project is the modeling and analytical evaluation related to PV system behavior, the problems identified in system operation and control, and the development of possible solutions to these problems.
FIVE SCENARIO SYSTEMS

WHITE NOISE

SPLINE

DIGITAL FILTER

\[ P_{\text{load}} \]

\[ P_{\text{noise}} \]

\[ P_{\text{PV}} \]

DYNAMICS

CLOUD BEHAVIOUR

P V ARRAY

CONTROL CENTER
REFERENCE
FREQUENCY

FAILSAFE
FREQUENCY
DEVIATION
LIMIT

AREA
FREQUENCY

FREQUENCY
DEVIATION
LIMIT

NET TIE
OUTFLOW

TIE SCHEDULE, MW

TIME

REFERENCE
FREQUENCY

FAILSAFE
FREQUENCY
DEVIATION
LIMIT

AREA
FREQUENCY

FREQUENCY
DEVIATION
LIMIT

NET TIE
OUTFLOW

TIE SCHEDULE, MW

TIME

K = AREA INDEX
i = UNIT INDEX
FIGURE 2.1  OVERVIEW OF AGC SIMULATION PROGRAM
AGCSIM PROGRAM

LOAD MODEL

AGCSIM

OUTPUT

freq vs t
P_{GI} vs t
P_{G2} vs t
... P_{GN} vs t
CONTROL vs t
PROJECT TASKS

1. Probabilistic Model of PV System Behavior
   (a) Weather effect model
   (b) Stochastic PV Behavior
   (c) Stochastic Load Behavior

2. PV System Impact on Utility Operation and Control
   (a) AGC, Unit Commitment and Spinning Reserve
       AGC Simulation
       Load Profile
   (b) NERC Control Guidelines
   (c) Ripple effect of disturbances

3. Solution to Problems created by PV Switching
   Control Strategies
   Protection Strategies

4. Final Report
SESSION II

Session Chairman: Hal Post
This presentation will provide an introduction to the array field engineering and subsystem research activities which will be reported upon at this session of the PIM. Significant progress in the reduction of array field balance-of-system (BOS) costs have been made during the past year. Modular flat-panel array fields have been installed in the Sandia test facility which demonstrate a four-fold decrease in the actual installation costs experienced in previous PV installations. Array field BOS costs for these modular designs are projected at $50/m² (1980$) of collector area for production quantities as low as 1 MW/yr. In a parallel effort, modular designs for concentrator systems covering a size range of 20-500 kW have also been developed. A contract has recently been placed to procure hardware for a modular concentrator array field consisting of six point-focus Fresnel arrays to be installed in the Sandia test facility by the end of CY83.

Development activities for large-size array fields have also made notable progress toward cost reduction. The integrated structure work has been completed with the installation of a prototype low-cost structure in the Sandia test facility. This structural design as well as a 2nd-generation concentrator array have been examined in detailed installation analyses in an effort to reduce costs through automated installation methods. Previous installation studies have shown that automated installation can be a viable cost reduction option. A major effort to examine system grounding and fault protection for large-size fields is nearing completion. This activity will culminate in the publication of a design manual which identifies methods, hardware, and code impacts. Lastly, the array field modularity work has been expanded to large-size systems to develop integrated and optimized designs appropriate for high-voltage, central station applications.
PROCUREMENT AND INSTALLATION
OF A
MODULAR PHOTOVOLTAIC ARRAY FIELD

by
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In the initial phase of a two-phase effort, a low-cost modular building-block design was developed which can be used in multiples for constructing intermediate-sized (e.g., 10-500 kW) flat-panel photovoltaic array fields. Costing by independent construction and electrical contractors indicates that the design is very cost effective when compared with previously developed designs, reducing the array-field balance-of-system costs (structure, wiring, etc.) to a fraction of those incurred in recent installations.

The general objective of this second-phase effort was to evaluate the building-block concept by installing, costing, and analyzing the performance of a PV array-field installation utilizing the developed building-block design. In addition, it is anticipated that the installation will provide a test bed for the long term evaluation of component reliability/durability, energy production, and general operating experience. The specific objectives of the major tasks of this phase of the project were:

- Procurement and/or fabrication of all electrical and structural components and PV modules for a modular 30-kW (nominal) array field, using the specifications and drawings developed during Phase 1.
- Installation of the 30-kW (3 building-blocks) array field at the site specified by Sandia at their Photovoltaic Advanced Systems Test Facility, Albuquerque, New Mexico.
- Testing of the installed array field to evaluate its performance under various operating conditions.

The second phase effort has been completed. The array field has been installed and placed in operation. Testing indicates that the building blocks will each produce approximately 10 kW under peak conditions. The installation was accomplished without major difficulty and within initial estimates of time and cost. The actual array-field balance-of-system costs of this first-time installation were approximately $134/m² in 1982 $ ($116/m² in 1980 $) to which $12/m² should be added for a security fence which would be required in most installations but already existed at the Sandia site. Analysis of the experience with this initial installation, based on detailed records of the time and manhours devoted to each activity, indicates that the cost of a second installation of the same size would be about $57/m² (1982 $) plus the fence cost. Larger fields using additional building blocks of the developed modular design permit substantial additional cost reductions.

A detailed engineering drawing package and construction specifications have been prepared and are available for use in installing array fields of various sizes using the developed modular design.
OBJECTIVE

TO EVALUATE THE BUILDING-BLOCK CONCEPT AND DESIGN DEVELOPED PREVIOUSLY FOR FLAT-PANEL ARRAY FIELDS—

• EASE OF INSTALLATION • COST • PERFORMANCE

APPROACH

PROCURE, FABRICATE, INSTALL, AND TEST A MODULAR ARRAY FIELD USING THREE BUILDING BLOCKS (~10 kW EACH) OF THE STANDARDIZED DEVELOPED DESIGN
CHARACTERISTICS OF THE MODULAR ARRAY FIELD BUILDING BLOCK DESIGN

- **PV MODULE**
  - 2x4 FT; 5 VDC OUTPUT
  - PARALLEL CELL STRINGS
  - BYPASS DIODE

- **FOUNDATION**
  - STEEL HAT-SECTION STAKES
  - WOLMANIZED 4x4 IN. BEAMS

- **STRUCTURE**
  - LIGHTWEIGHT STEEL ANGLE AND TUBING
  - TWO-MODULE PANEL, 4x4 FT

- **BRANCH CIRCUIT**
  - ~10 kW PEAK OUTPUT @NOCT AND 10% EFFICIENT MODULES
  - ~400 VDC @NOCT
  - 2 MODULES IN PARALLEL, 82 PAIRS IN SERIES

- **INTERMODULE WIRING**
  - CRIMP-SPICED PIGTAILS WITH INSULATING PAD

- **FIELD WIRING**
  - DIRECT BURIAL CABLES

- **BUILDING BLOCK SIZE**
  - ~10 kW PEAK OUTPUT @NOCT
  - ~400 VDC @NOCT
  - TWO ROWS OF STRUCTURE
  - ~165 FT EAST-WEST BY 18 FT NORTH-SOUTH WITH AISLES
LOW-COST STRUCTURE/FOUNDAITION DEVELOPED BY BATTELLE
FOR THE ARRAY-FIELD BUILDING-BLOCK DESIGN
KEY FEATURES OF THE STRUCTURE/FOUNDATION DESIGN

• FABRICATED AT MINIMUM COST USING SIMPLE PARTS

• COMPONENTS IMMEDIATELY AVAILABLE WITHOUT DEVELOPMENT

• ACCOMMODATES SITES WITH UNEVEN TERRAIN (MINIMUM SITE PREPARATION)

• CONTINUOUS METAL STRUCTURE REDUCES GROUNDING COSTS

• ALL COMPONENTS CAN BE HANDLED BY ONE PERSON

• EASILY ACCESSIBLE FOR CLEANING/MAINTENANCE FROM GROUND LEVEL

• SIMPLY AUTOMATED WITH MINIMUM CAPITAL INVESTMENT
WIRING AND GROUNDING FOR BUILDING BLOCK DESIGN

- JUNCTION BOX -1 PER BRANCH CIRCUIT
- NEGATIVE (-) LEAD FROM SOUTH ROW
- ROW END INTERCONNECTION
- COUNTERPOISE FOR SITE GROUNDING
- 10 FT GROUNDING STAKES - TYPICAL OF SIX
- TO GROUNDING STAKES ON NEXT BRANCH CIRCUIT OR FENCE

DETAIL A

CRIMP-SPlice CONNECTOR WITH ADHESIVE PAD INSULATION (SERIES-PARALLEL CONNECTION FOR 4 MODULES)

5-VOLT PV MODULE WITH INTEGRAL BYPASS DIODES (2 FT X 4 FT)

TWO MODULES IN PARALLEL
IN SERIES WITH
TWO MODULES IN PARALLEL
IN SERIES WITH
TWO MODULES IN PARALLEL

BRANCH CIRCUIT/BUILDING BLOCK
(1 BRANCH CIRCUIT = 1 BUILDING BLOCK)
- 400 VDC • 24.4 A TYPICAL
- 9.75 kW (800 W/m², NOCT, 10% EFFICIENCY)
- 164 PV MODULES, 2 MODULES (IN PARALLEL) PER PANEL
KEY FEATURES OF THE ELECTRICAL DESIGN

• MINIMIZES EFFECT OF CELL FAILURES ON OUTPUT
• LOW MAINTENANCE AND LIFE CYCLE COSTS
• LOW MODULE-INTERCONNECTION COSTS
• USES STRUCTURAL COMPONENTS FOR GROUNDING
• IN-FIELD PROVISION FOR ISOLATION AND TESTING

ARRAY TESTING PLAN

MEASUREMENTS

• CONTINUOUS LOAD (INCLUDING \( V_{oc} \) AND \( I_{sc} \))
• FULL I-V (INDIVIDUAL BUILDING BLOCKS AND PARALLEL COMBINATION)
• SHADING EFFECTS
• CELL OPERATING TEMPERATURES
• BLOCKING DIODE LOSSES
• WEATHER AND INSOLATION DATA

EQUIPMENT

• MODEL PV 500-40 IV CURVE TRACER
• HP 85 MICROPROCESSOR
• DIESEL GENERATOR LOAD BANK
ARRAY TESTING RESULTS

Measurements on BB #1 and BB #2 Individually Just After This Data Was Taken Yielded the Following Data

BB #1
- $V_{oc} = 485$ V
- $I_{sc} = 25.8$ A
- $P_{max} = 8331$ W (367 V @ 22.6 A)

BB #2
- $V_{oc} = 483$ V
- $I_{sc} = 26.2$ A
- $P_{max} = 8421$ W (369 V @ 22.8 A)

LOAD BANK DATA BB #1 + BB #2
1/19/83 - 12:42 PM MST

$V_{oc} = 481.2$ V

15931 W
(327.2 V @ 48.7 A)

16650 W
(370 V @ 45 A)

$T_{ambient} = 10$ C
$T_{cell} = 31$ C
INSOL = 907 w/m²
MODULAR PHOTOVOLTAIC ARRAY FIELD
SANDIA CONTRACT NO. 68-3152

GEORGE J. NAFF
HUGHES AIRCRAFT COMPANY, SUPPORT SYSTEMS
P.O. BOX 9399
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APRIL 1983
MODULAR PHOTOVOLTAIC ARRAY FIELD
SANDIA CONTRACT NO. 68-3152
George J. Naff
Hughes Aircraft Company, Support Systems
P.O. Box 9399
Long Beach, CA 90810-0399

Under contract with Sandia National Laboratories during calendar year 1981, the Hughes Aircraft Company carried out analyses, designs and life cycle cost trade-offs which lead to an optimized, modular, intermediate power (20 to 500 kWp), grid interactive photovoltaic array field. This design study addressed primarily the balance of systems (BOS) elements of the array field; the photovoltaic conversion devices (cells and modules) are to conform to the JPL Block V Specifications No. 5101-161. The power inversion device was not addressed.

The BOS element categories included (a) the array structures and foundations, (b) array field wiring topologies, (c) power collection, (d) electrical protection and safety, and (e) site preparation and security. Photovoltaic modules were cost analyzed on the basis of size, wiring topology, electrical protection, panel configurations, installation, reliability and maintainability, and expected life. Matrices of various combinations of BOS element designs were analyzed using a computerized cost breakdown structure program; trade-offs were carried out to achieve optimized 20 year life cycle system costs for array field sizes of 20, 100 and 500 kWp. From these BOS elements one final design was configured to satisfy modular expansion in the intermediate power range of 20 to 500 kWp. System modularity was established at a nominal 10 kWp source circuit. Manufacturing cost estimates were based upon annual production rates of ten megawatts.

To verify the modular design, Sandia contracted with Hughes in 1982 to construct a 30 kWp array field, three source circuits. The manufacturing drawings and procurement specifications developed for the final design were used verbatim, without change. Except for the Hughes fabricated parts, all hardware, material and subcontract procurements were procured under open competitive bid procedures.

The 30 kWp array, depicted in Figure 1 is summed from the three 10 kWp source circuit building blocks, each source developing + 200 Vdc in a bipolar configuration. Power from each half row is terminated in a small junction box, Figures 2 and 3, located at the inner end of each pole row before being routed underground to the system Power Collection Center (PCC) located at the rear center of the array field. One PCC is capable of handling up to 10 source circuits (100 kWp) before being replicated. The PCC includes the electrical switch gear, the electrical protection and grounding components, and up to five power control modules, each capable of independently controlling two source circuits. System power to an inverter is available at the main lugs within the PCC. The PCC and its schematic are depicted in Figures 4 and 5.
Four each, two foot by four foot, 5 volt photovoltaic modules, form a panel. The modules are wired in a horizontal folded daisy chain configuration, Figure 6, by the use of jumper cables terminating into male plugs which in turn mate into receptacles factory mounted onto the PV module busbar by the module manufacturer.

A hybrid array foundation consisting of front buried metal feet and a concrete curb at the rear provides the support for the PV panel support structures. The front metal feet provide self grounding for the array structures. The PV panels are mounted to front and rear foundation stanchions, Figure 7. The array grounding counterpoise is laid in the same trenches prepared for the buried field cables.

The array field site preparation, trenching, concrete work, assembly and installation of structures were performed by a local Albuquerque general contractor. Structures and electrical parts were fabricated in the Los Angeles area and shipped to site. The photovoltaic modules were subjected to selected qualification tests per JPL Block V Specification 5101-161 at an independent testing facility. Production modules were source inspected at the manufacturer's facility and verified by lot sample testing at the Hughes facility. The photovoltaic modules were assembled into panels at the site maintaining module current matching to within 0.25 amps per string (one-fourth of a source circuit). I-V curves, Figures 8 and 9, were generated.

Except for delays in receipt of vendor furnished parts or delays due to inclement weather at the site, the procurement, fabrication, installation and test went according to plan and in some phases much better than expected.

A cost breakdown, Table 1, shows BOS costs for this 30 kWp array at $163.11 per square meter of array.

<table>
<thead>
<tr>
<th></th>
<th>$/M²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTRICAL HARDWARE</td>
<td>$28.98</td>
</tr>
<tr>
<td>STRUCTURES/FOUNDATIONS HARDWARE</td>
<td>$21.66</td>
</tr>
<tr>
<td>FIELD INSTALLATION</td>
<td>$112.47 *</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$163.11 (1982 $)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$140.92 (1980 $)</td>
</tr>
</tbody>
</table>

* INCLUDES PRICE FOR FENCE
480 PV MODULES
120 PV PANELS

(2) 200 Vdc SOURCE CIRCUITS

OUTPUT: 27.6 kW AT SOC
34.5 kW AT 1000 W/m², NOCT

FIGURE 1 MODULARIZED NOMINAL 30 kWp ARRAY FIELD LAYOUT
FIGURE 2 TYPICAL J-BOX
FIGURE 3 BUILDING BLOCK JUNCTION BOX SCHEMATIC
FIGURE 4  POWER COLLECTION CENTER (PCC)
FIGURE 5 POWER COLLECTION CENTER (PCC) SCHEMATIC
DAISY CHAIN FOLDED 5 VOLT MODULES

JUNCTION BOX—2 PER BRANCH CIRCUIT

TO POWER COLLECTION CENTER

(+)

N

(-)

VIEW A

PV PANEL 4 MODULES

PV PANEL 4 MODULES

2 ft x 4 ft PV

5 VOLT MODULE

SOURCE CIRCUIT

±200 VDC @28 AMPS
11.5 kW (1000 W/m² AT NOCT)
40 PV PANELS
4 MODULES PER PANEL
160 MODULES

MODULE TO MODULE DAISY CHAIN WIRING

SOLAR-LOK CONNECTOR

FIGURE 6 11.5 kW ± 200 V BIPOLAR ARRAY FIELD BUILDING BLOCK
FIGURE 7 STRUCTURE HYBRID FOUNDATION ASSEMBLY AND PANEL ASSEMBLY
Figure 8 I-V Curve, One Source Circuit Pole, (Two Strings in Parallel)

EAU corrected to AM 1.5, 1000 W/m², 25°C

- $I_{sc} = 14.2$ AMPS
- $I_{mp} = 12.4$ AMPS
- $V_{mp} = 211$ VOLTS
- $V_{oc} = 264$ WATTS
- $P_{mp} = 2611$ WATTS

CEL T = 81 DEG F
AMB T = 50 DEG F
$I_{so} = 947$ mW/cm²
BRANCH # H9- EAU 11:37 MST
$V_{oc} = 260$, $I_{sc} = 13.5$ amps
$P_{max} = 2442$, $V_{oc} = 207$, $I_{mp} = 11.7 A$
EAP corrected to AM 1.5, W/M², 25°C

$I_{sc} = 28.4$ AMPS

$I_{mp} = 25.5$ AMPS

$V_{mp} = 204$ VOLTS

$V_{oc} = 261$ VOLTS

$P_{mp} = 5209$ WATTS

**FIGURE 9** STRING I-V CURVE, ONE HALF POLE (40 PV MODULES IN SERIES)
PHOTOVOLTAIC SYSTEM GROUNDING
AND FAULT PROTECTION STUDY

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Bechtel Group, Inc., under a contract with Sandia National Laboratories, is conducting a study of grounding and dc system fault protection in photovoltaic power systems. The emphasis of the study is on large (1 to 1000 MW) central station type plants with medium-sized (20 to 1000 kW) systems also addressed. In addition, United Technologies Corporation (UTC), under subcontract to Bechtel, is evaluating the requirements for PCS isolation transformers in medium-sized systems. UTC is also contributing to the grounding/fault protection study.

Current practices in other technologies and existing codes were reviewed for relevance and applicability to photovoltaic power plants. A set of design criteria was developed. Important among these criteria is the voltage limit allowable for possible personnel exposure during fault (and normal) conditions. This element of design along with requirements for operation of relaying require grounding and fault protection design to be considered simultaneously.

Evaluation of plant and system designs indicated that lightning protection and faults in the plant ac substation may influence grounding system design more than the dc system. The design of the grounding system is also strongly influenced by items beyond the control of the designer (e.g., soil resistivity). Overall costs can be reduced by integrating the grounding system with other plant subsystems. Examples of this are the use of rebar in concrete array foundations as ground rods, the use of foundation and wiring excavations to bury grounding cables, and the use of array structural elements (e.g., torque tubes in flat plate arrays) to form part of the ground system.

In the area of dc fault protection, a computer program was used to estimate fault current for postulated subfield and dc wiring configurations. Protection circuit configurations and equipment were evaluated. Surge protection and the interaction of the PCS were also evaluated. Vendors and manufacturers were contacted to catalog the characteristics of currently-available sensors and protective devices needed to meet system design requirements.
TASKS

GROUNDING SYSTEM REQUIREMENTS DEFINITION

GROUNDING SYSTEM DESIGN GUIDELINES AND ANALYSIS

SYSTEM FAULT PROTECTION ANALYSIS

RECOMMENDED PRACTICES AND CODE IMPACTS

FINAL REPORT / DESIGN GUIDE
SURFACE VOLTAGE PROFILES

GROUND GRID POTENTIAL

EARTH SURFACE POTENTIAL

POTENTIAL DIFFERENCE (VOLTAGE)

0.11 VOLTS PER AMP OF FAULT CURRENT

% SECTION OF SMUD 1 MW PLANT

A

B

CONTROL BUILD

SUBSTATION
COMPLETE ARRAYS:

FOUNDATION AND ASSEMBLY ELEVATION:

END VIEW

DETAIL OF EARTHING CONNECTION

PV FLAT PLATE ARRAY
MIDPOINT CURRENTS TO GROUND FOR A 5.0 MW 2,000 V SUBFIELD

\[ R_2 = R_2/(N-1) \]

\[ N \text{ CIRCUITS IN PARALLEL} \]

\[ \text{ONE CIRCUIT} \]

\[ R_2 = 0 \text{ OHMS} \]

CURRENT IN MIDPOINT OF FAULTED CIRCUIT

CURRENT IN MIDPOINT OF ANY UNFAULTED CIRCUIT

CURRENT IN MIDPOINT RESISTORS, \( R_2 \)

CURRENT IN MIDPOINT OF FAULTED CIRCUIT

CURRENT IN MIDPOINT OF ANY UNFAULTED CIRCUIT

CURRENT IN MIDPOINT RESISTORS, \( R_2 \)

CURRENT IN MIDPOINT OF FAULTED CIRCUIT

CURRENT IN MIDPOINT OF ANY UNFAULTED CIRCUIT

GROUND FAULT LOCATION
CURRENT AND POWER THRU MIDPOINT GROUNDING RESISTOR, WITH LOAD REMOVED (OPEN CIRCUIT) AND FAULT TO GROUND

LOW RESISTANCES

HIGH RESISTANCES
PCS ISOLATION TRANSFORMER

ADVANTAGES:

- Dc System Voltage and Power Levels
- Dc Injection
- Grounding
- Harmonics
- Safety
- Utilities and Standards Committees

DISADVANTAGES:

- Cost
- Size and Weight
- Efficiency
During the past three years, Burt Hill Kosar Rittelmann Associates has been actively investigating the use of mechanized/automated equipment for the installation of large photovoltaic arrays. The current study which has been underway since August of 1982 has focused on the development of equipment for the installation of two types of photovoltaic array fields:

- The Martin-Marietta Point Focused Fresnel Lens System
- The Bechtel Torque Tube with Two Point Support System

The study has focused on the development of scenarios and costs using standard installation procedures, the identification and development of equipment to mechanize/automate various steps in the installation scenario and to identify the new installation costs associated with the mechanized/automated installation scenario. Based on the standard installation cost data and the expected equipment cost for the mechanized/automated installation scenario, it appears that the development of such equipment for a class of support systems and panel types can be cost justifiable.

The results reported in this study include the installation costs associated with the standard installation scenarios for both the flat plate and concentrator array fields. This data is provided as a total cost, as a cost per square meter of aperture area, and as a cost per kilowatt hour of annual production. It is important to note that the costs generated here are only the array field costs and do not include the cost of the photovoltaic panels or arrays, the power conditioning equipment and the associated AC switchgear and transmission lines found on the output side of the power conditioning unit. The costs do include land and site preparation, support structure installation, array field wiring and panel/array installation. This data, when combined with the remaining balance of system costs, will permit the identification of the most cost effective array field approach when comparing the two studied systems.

In addition to the above data, the study includes details on the equipment costs and installation costs of the concentrator and flat plate array field installation using mechanized/automated techniques. Again, these installation costs do not include the cost of the power conditioning equipment and the cost associated with the AC output side of the power conditioning equipment. In addition, the developmental costs are projected for the hardware as developed and described for the installation of photovoltaic array fields.

Several basic conclusions can be drawn at this point in time with regard to the installation of the two studied array field types. It is evident at this point that significant concentrator array field costs center around the array field wiring; the high cost resulting primarily from the wire cost, the need to bury the secondary wiring; the need for AC and control wiring; and the need for a large number of junction boxes for electrical interconnects. It also appears that the costs associated with the installation of both the flat plate and the concentrator array fields can be reduced via the use of mechanized/automated installation techniques. In addition, the equipment necessary for the installation of photovoltaic arrays can be developed and purchased at a cost which is economically advantageous to the owner of a large photovoltaic array field. Finally, it appears that additional strides must be made at integrating the design of photovoltaic systems and array fields to further reduce the installed costs of photovoltaic power systems.

It is anticipated that the remaining portions of this study will be completed during late Spring and the final report will be submitted to Sandia for review in early Summer.
AUTOMATED INSTALLATION METHODS
FOR PHOTOVOLTAIC ARRAYS

Objectives

- Develop automated equipment concepts which reduce installation time and labor requirements
  - Bechtel flat panel array
  - Martin Marietta concentrator array
- Estimate the costs of the equipment

Scope

- Review the panel and field designs
- Produce automated installation scenarios
- Prepare equipment cost and advance conceptual design documentation
  - Support installation
  - Panel installation
12"x12"x.500" STEEL PLATE

10"x .188 STEEL PIPE

.625"x2" STEEL STUDS

3000 PSI CONCRETE

CONCRETE ENCASED STEEL TUBE

12"x12" .500" STEEL PLATE

10"x .188" STEEL PIPE

.625"x2" STEEL STUDS

3000 PSI CONCRETE

RE-BAR CAGE

MODIFIED STEEL TUBE/RE-BAR CAGE

SUPPORT STRUCTURES
### 10 MW ARRAY FIELD CHARACTERISTICS

<table>
<thead>
<tr>
<th>ARRAY TYPE</th>
<th>CONCENTRATOR</th>
<th>FLAT PLATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARRAY SIZE</td>
<td>10.7' X 44.4' = 475 ft² (44.1 m²)</td>
<td>8.3' X 39.0' = 324 ft² (28.9 m²)</td>
</tr>
<tr>
<td>APERTURE AREA (EACH ARRAY)</td>
<td>388 ft² (36.0 m²)</td>
<td>277 ft² (25.7 m²)</td>
</tr>
<tr>
<td>TOTAL NO. OF ARRAYS</td>
<td>50/SUBGROUP X 48 SUBGROUPS 2,400 ARRAYS</td>
<td>120 SUBGROUP X 36 SUBGROUPS 4,320 ARRAYS</td>
</tr>
<tr>
<td>TOTAL ARRAY FIELD AREA</td>
<td>214 ACRES (86.6 HECTARES)</td>
<td>122 ACRES (49.4 HECTARES)</td>
</tr>
<tr>
<td>TOTAL AREA REQUIRED/ARRAY</td>
<td>3,884 ft² (360.9 m²)</td>
<td>1,230 ft² (114.3 m²)</td>
</tr>
</tbody>
</table>

### 10 MW ARRAY FIELD INSTALLED COSTS

<table>
<thead>
<tr>
<th>ARRAY TYPE</th>
<th>CONCENTRATOR</th>
<th>FLAT PLATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE PREPARATION &amp; DRAINAGE</td>
<td>$726,713</td>
<td>$467,814</td>
</tr>
<tr>
<td>ARRAY FIELD WIRING</td>
<td>3,396,250</td>
<td>973,319</td>
</tr>
<tr>
<td>SUPPORT STRUCTURE</td>
<td>817,868</td>
<td>1,066,961</td>
</tr>
<tr>
<td>ARRAY INSTALLATION</td>
<td>413,108</td>
<td>504,018</td>
</tr>
<tr>
<td>TOTAL COST</td>
<td>$5,353,939</td>
<td>$3,012,112</td>
</tr>
<tr>
<td>$/m²</td>
<td>$61.97/m²</td>
<td>$27.18/m²</td>
</tr>
<tr>
<td>$/kWh/FIRST YEAR</td>
<td>$0.173</td>
<td>$0.127</td>
</tr>
</tbody>
</table>
CONCENTRATOR (849 KW PEAK)
WIRING SCHEMATIC

FLAT PLATE (291 KW PEAK)
WIRING SCHEMATIC
SUPPORT INSTALLATION POSITIONING

Target Positions
△ = Augering
□ = Support Setting

Typical Path Shape For
Mid-Course Correction (Exaggerated)

Vehicle Position Targets
Vehicle Setting Support in Hole

Vehicle Augering "Next" Hole

Control Vehicle
(See Inset)

Target Sighting Lines
CONCLUSIONS

- Significant concentrator array field costs center around the array field wiring resulting from:
  - Large quantity of wire
  - Need to bury secondary wiring
  - Need for AC & control wiring
  - Large quantity of J-boxes & electrical interconnects

- Cost can be reduced via mechanized/automated installation techniques.

- Continued integration of photovoltaic systems and array fields is required to further reduce the installed costs of photovoltaic power systems.
The objective of this project is to perform additional subsystems optimization studies on a previously developed flat-panel array-field building-block design developed under Contract 62-9187, "Photovoltaic Array Field Optimization and Modularity Study". The emphasis in this project is on

- Larger array fields for central station applications
- Appropriate system and personnel protection requirements
- Modifications to the existing structural design associated with larger size array fields and a longer service life
- Modifications appropriate for longer term (i.e., 1986) implementation.

The specific objectives of the major tasks are:

- Task 1. Array Structure and Foundation Analysis and Design - to examine, analyze, and modify the array-field structural and foundation designs to meet the requirements of central station applications at minimum cost.
- Task 2. Field Electrical Wiring Analysis and Design - to develop an overall array-field wiring design to meet central station application requirements at minimum life-cycle energy cost.
- Task 3. Design Integration and Building-Block Identification - to interrelate continuously the results of Tasks 1 and 2 to produce a fully integrated building-block design reflecting both structural and electrical requirements and considerations.
- Task 4. Preparation of Engineering Drawing Packages, Specifications, and Costs - to prepare detailed engineering drawings and specifications for the building-block design; to prepare detailed structural, electrical, and site drawings for modular 1-, 10-, and 100-mW array fields using the building-block design; and to prepare cost estimates based on the drawings and specifications.

A baseline circuit design has been developed as a result of array circuit design and analysis studies. Features of the design include:

- Series Block--11 series cells per string; 24 parallel strings; 1 bypass diode
- Branch Circuits--400 series blocks; 2000 v; approximately 120 kWp
- 1 MW (NOC) Building-Block--13 parallel-connected branch circuits
- 5 MW (NOC) Building-Block--63 parallel-connected branch circuits.
The branch circuit will be center-tap grounded, yielding array end-point voltages of ±1000 volts with respect to ground. The circuit will be implemented with 2 x 4-ft modules (4 per series block) but is compatible with 4 x 4-ft modules if they are available and cost effective.

The baseline circuit design leads to a support structure concept with an 8-ft slant height. Several candidate structural concepts were reviewed with an emphasis on comparative costs. Factors of concern in evaluating structural concepts include: ability to adjust for tolerance buildup, ability to accommodate thermal expansion effects, and compatibility with anticipated terrain variations.

Screening of candidate conceptual designs of structures for use with framed PV modules has been completed and a concept has been selected for additional analysis and cost evaluations. The selected concept is an extension of the design developed in a previous study for intermediate-sized array fields. The major factors contributing to the evolution of that original design to the concept presently being evaluated are the requirement of a minimum operating life of 30 years and the assumption of the availability of specially designed automated equipment for the installation. The design being further developed utilizes precast concrete foundations, steel angle module supports, and tubular metal struts. Detailed analyses have been performed to assure compliance with specifications for withstanding wind load and other forces. Cost analyses are also being performed.

Preliminary designs of the electrical and physical layouts for the 1 MW and 5 MW building blocks have been developed. Analyses of electrical design requirements (e.g., wire sizes required to comply with maximum allowable losses, economic tradeoffs for larger sizes, etc.) and options have proceeded as planned. Identifying appropriate electrical hardware which is rated for the branch circuit current and voltage levels and which is compatible with the cost objectives has posed some difficulties.
OBJECTIVE

BASED ON THE LOW-COST MODULAR DESIGN DEVELOPED FOR FLAT-PANEL PV ARRAY FIELDS OF 20-500 kW-PEAK, THE OBJECTIVE OF THIS PROGRAM IS TO PERFORM ADDITIONAL SUBSYSTEMS OPTIMIZATION EFFORTS WITH EMPHASIS ON:

- LARGER ARRAY FIELDS FOR CENTRAL-STATION APPLICATIONS (1-100 MW)
- HIGHER FIELD VOLTAGES
- APPROPRIATELY MODIFIED PROTECTION REQUIREMENTS
- INCREASED VERSATILITY AND LIFETIME FOR THE DEVELOPED STRUCTURAL DESIGN
- MODIFICATIONS FOR LONGER RANGE (1986) IMPLEMENTATION
SCOPE

• DEVELOP A MODULAR BUILDING-BLOCK DESIGN FOR USE IN INSTALLING 1-100 MW CENTRAL-STATION ARRAY FIELDS AT MINIMUM LCC

• DESIGN 1-MW, 10-MW, AND 100-MW ARRAY-FIELD LAYOUTS USING THE DEVELOPED BUILDING BLOCK

• PROVIDE DETAILED WORKING DRAWINGS, CONSTRUCTION SPECIFICATIONS, AND COST ESTIMATES FOR THE DEVELOPED DESIGN
MODIFIED REQUIREMENTS FOR CENTRAL-STATION APPLICATIONS

THE ARRAY-FIELD DESIGN SHOULD HAVE:

- OPERATING LIFE OF 30 YEARS OR GREATER
- CONCRETE AS ONLY MATERIAL BELOW GROUND LEVEL
- NO WOOD COMPONENTS
- ACCOMMODATIONS FOR LARGER MODULES (E.G., 2 x 4 FT, 4 x 4 FT, 4 x 8 FT)

ALSO, THE LARGE FIELD SIZES AND 1986 IMPLEMENTATION PERMIT AUTOMATED EQUIPMENT FOR INSTALLATION
PRESENT STATUS OF STRUCTURAL DESIGN

THE STRUCTURE/FOUNDATION DESIGN BEING DEVELOPED HAS

• 8 FT SLANT HEIGHT
• 18 FT ROW SPACING
• SHARED PRECAST CONCRETE FOUNDATION
• LIGHT-GAUGE STEEL-ANGLE SUPPORT RAILS
• CONDUIT-TUBE BACK STRUTS
FEATURES OF PRESENT STRUCTURAL DESIGN

SIMPLE EFFICIENT INSTALLATION

CONCRETE FOUNDATIONS

STEEL STRUCTURE

THERMAL EXPANSION ABSORBED BY ANGLE DEFLECTION AT EACH BAY

CONTINUOUS GROUND STRUCTURE (MINIMIZES EXTRA WIRES)

CONTINUOUS CONSTRUCTION—ELIMINATES TOLERANCE STACK PROBLEMS (PANEL INSTALLED AND TIGHTENED BEFORE FOUNDATION FIXED VIA EARTH TAMPING)

RELATIVELY INEXPENSIVE AUTOMATION OF FIELD AND ROW LAYOUT, AND INSTALLATION

WITHSTAND ALL ENVIRONMENTAL CONDITIONS OF ORIGINAL OPTIMIZATION AND MODULARITY STUDY INCLUDING:
  • FULL WIND AT EDGE OF FIELD WITH NO FENCE
  • COMBINED WIND, SNOW, AND ICE LOADS
CONCRETE PIER DETAIL
N.T.S.

2

36" PRECAST CONCRETE (3500 F'') 6"x6" SECTION
127 LBS. W/ 2"x 3/16" x 40" S.S. BAR
= 4.27 LBS
131 LBS. TOTAL PER UNIT

2" x 3/16" x 40" S.S. BAR

4 - 1/4" T TRANSVERSE CRIMPS AT BOTTOM OF S.S. BAR

SIDE VIEW
EDGE VIEW
SOURCE CIRCUIT
DESIGN DEVELOPED

400 SERIES BLOCKS—1600 MODULES

LENGTH = 488 m

APERTURE = 1189 m²

RATED OUTPUT (NOMINAL 10% EFFICIENCY)

- 2000 V x 60 A = 120 kW PEAK
- 1716 V x 48 A = 82.4 kW NOC
1 MW BUILDING BLOCK DESIGN

13 PARALLEL-CONNECTED SOURCE CIRCUITS

15,460 m² APERTURE

DC (ARRAY FIELD) RATING
- 2000 V x 780 A = 1,560 kW PEAK
- 1716 V x 624 A = 1,071 kW NOC

1 MW POWER CONDITIONING UNIT

OUTPUT—13.8 kV, 3 φ, 60 Hz
5 MW BUILDING BLOCK DESIGN

63 PARALLEL-CONNECTED SOURCE CIRCUITS

74,919 m² APERTURE

ARRAY-FIELD RATING (DC)

• 2000 V x 3780 A = 7,560 kW PEAK
• 1716 V x 3024 A = 5,189 kW NOC

5 MW POWER CONDITIONING UNIT

OUTPUT—34.5 kV, 3 φ, 60 Hz
SESSION III

Session Chairman: Tom Key
Power Conditioning Session Introduction

Power Conditioning Technology for Grid-Connected Applications

During the last year, major progress has been made with respect to performance and low-cost potential for PV power conditioners. This is particularly true for the small (2-10 kW) residential type units. Interface and control problems related to adapting available inverter designs to grid-connected residential experiments are now solved. Four promising design concepts have been identified and several advanced power conditioners that apply to these concepts have been developed specifically for PV applications. There are at least six manufacturers currently marketing grid-connected power conditioners for PV.

Among several advanced concepts that have been developed into working hardware, the high-frequency link approach has demonstrated the greatest reduction in size and weight. In this approach, the large and heavy 60 HZ isolation transformer is replaced by a 10-150 KHZ transformer that is many times smaller for an equivalent power handling capability. Three conversion steps are required in the HF link design. First, the dc from the array is inverted into a symmetrical pattern of pulses using two or four solid state switches. This pattern is usually modulated to carry the 60 HZ sine wave shape through the HF link transformer. The pulses are then rectified after passing through the transformer and shaped into half-sine waves by a series reactor. They are then unfolded or inverted into the utility line using a full-bridge inverter.

The efficiency of this approach is about the same (~92%) as other advanced approaches that use 60 HZ transformers. However, the size and weight is reduced substantially. The potential for low-cost production is therefore increased.

The cost experience to date with advanced residential PCS hardware is 3-5 times the DOE suggested allocation of $.20-.30/Wp for a PCS in an "economical" PV system. Future technical advances including compact and powerful micro-processor control, integrated power switching modules and improved magnetic materials will reduce cost relative to the designs that are available today. However, major cost decrease is expected to come from a transition to volume production.
I. TESLAco INVERTER: DESIGN CONCEPT AND FEATURES

The TESLAco inverter was designed specifically for line tied applications and takes advantage of this by using a topology that only allows a forward power flow (Fig. 1). This topology incorporates a high frequency (20kHz) isolation transformer for substantial savings in size and weight. The 4kW transformer weighs only 2.5 lbs. compared to about 50 lbs. for the 60Hz equivalent. The two main switches Q1 and Q2 are single Darlington transistors for simplicity and can withstand input voltages up to 700V. The output unfolding bridge is very efficient as it only switches at the current and voltage zero crossings. The components chosen for this application were high safe operating area (800V, 90A) transistors which allow the output to be protected from virtually any line waveform without the need for fuses.

Fig. 1 Basic Topology of TESLAco Inverter
II. PROTOTYPE SPECIFICATIONS AND TEST RESULTS (Fig. 2)

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Power:</td>
<td>4kW</td>
</tr>
<tr>
<td>Input Voltage, Operating:</td>
<td>160 to 240V</td>
</tr>
<tr>
<td>Input Voltage, Withstand:</td>
<td>0 to 600V</td>
</tr>
<tr>
<td>Output Voltage:</td>
<td>240VAC ±5%</td>
</tr>
<tr>
<td>Ambient Temperature:</td>
<td>-10 to +45°C</td>
</tr>
<tr>
<td>Size:</td>
<td>20&quot; x 6.5&quot; x 13.5&quot;</td>
</tr>
<tr>
<td>Weight:</td>
<td>38 lbs.</td>
</tr>
<tr>
<td>Cooling:</td>
<td>Forced air over external heatsinks, convection cooled cabinet.</td>
</tr>
<tr>
<td>Efficiency (full output):</td>
<td>92%</td>
</tr>
<tr>
<td>Standby Power Dissipation:</td>
<td>2.5W</td>
</tr>
<tr>
<td>Output Current Distortion:</td>
<td>3.5% on a 1.2% distorted line.</td>
</tr>
</tbody>
</table>

![Fig. 2 Output current at 4kW, 10A/div., 5ms/div.](image)

III. INVERTER CONTROL OVERVIEW

Fig. 3 shows a simplified block diagram of a feedback structure. The unfolding stage is always controlled by the voltage zero crossings of the 240V line. This minimizes the possibility of the unfolding transistors shorting the line. The output of the buck stage is derived from a digitally generated sine reference produced by a PLL circuit that locks into the 60Hz line. During normal operation, the input voltage control circuit acts so as to null the error signal from the peak power tracker. However, when the array peak power point lies above 240V or below 160V, the peak power tracker error signal will be overridden so as to maintain the array voltage between these limits. The peak power tracker will also be overridden if the current into the 240V ac line exceeds 17A rms (corresponding to 4kW). In this situation, the array voltage will be increased to a level greater than the peak power point until the output current is within 17A rms. In this mode, the input voltage may be allowed to go up to at least 250V.
Fig. 3 Simplified Control Block Diagram
Fig. 4  Block Diagram Showing Control Structure and Gains.
A more detailed diagram of the control structure is shown in Fig. 4 where the actual small signal gains of the function blocks are given. Note that the buck PWM Control of Fig. 3 actually contains a minor feedback loop that subtracts the buck stage output current from the AM sine signal. The purpose of this is to make the entire inverter present a 6Ω resistive impedance (approx.) to the 240VAC line for frequencies above 60Hz. The sample and hold circuit in the feedback circuit reduces the distortion of the 60Hz output by preventing the input voltage control feedback loops from interfering with the minor loop around the buck stage. With this setup, the inverter output current is governed by the 6Ω resistive impedance during each 60Hz cycle, but its rms value in the long term is dictated by the input voltage control feedback loops.

IV. PROTECTION AND SEQUENCING

The inverter control logic differentiates between 2 types of error conditions. Type 1 errors result in the buck stage and unfolder switches being turned off immediately. The inverter will restart approximately 30sec after these error conditions are removed. Type 2 errors have no immediate effect, but will result in the inverter going into low power standby mode if they persist for more than approximately 60sec.

Type 1 Errors: Output overcurrent
(immediate shutdown)
Buck stage extreme overcurrent
Line voltage out of tolerance
Input overvoltage
Excessive PLL phase error
Heatsink over temperature

Type 2 Errors: Input current too low
(standby mode)
Line voltage out of tolerance
Excessive PLL phase error

When a given error condition is listed under both categories, it will produce both responses.

V. BUCK STAGE CONTROL

The push-pull buck stage is operated without any voltage feedback since various line impedances could produce stability problems with a voltage feedback loop. With direct PWM control, the voltage gain of the buck stage would be proportional to the array voltage. In order to cancel this effect, the slope of the modulator ramp is made proportional to the dc input voltage (Fig. 5). This feed-forward compensation makes the control voltage to output gain of the buck stage independent of the array voltage. The current feedback loop subtracts a voltage proportional to the collector currents from the control voltage. The return ratio of this feedback loop is chosen so as to produce a low frequency output impedance of 6Ω for the entire buck stage. The output impedance measurements (Fig. 7) show that the low frequency output impedance of the inverter is indeed approximately 6Ω. At higher frequencies, the reactances of the output filters also contribute to the output impedance, but the LC resonances are still damped by the 6Ω resistive output impedance of the buck stage. This can be modelled as being in series with the 1.2mH inductor (Fig. 6). Note that the 6Ω output resistance is non-dissipative and allows the harmonic currents resulting from a distorted line to be kept under control. The flux sense control block of the buck stage adjusts the symmetry of the alternate PWM pulses so as to maintain the flux level in the transformer between predetermined limits. This eliminates the possibility of saturating the power transformer.
Fig. 5  Buck Stage Control Structure
Fig. 7 Output Impedance Measurements (sharp spikes are due to Instrumentation noise).
The current limit loop will clip the sinusoidal output current waveform at approximately 25A. Such clipping will only occur during transient conditions or when the ac line is badly distorted. Under normal operating conditions, the other system feedback loops maintain the buck stage within its linear range.

Fig. 6 Model of Buck Stage Output

VI. PEAK POWER TRACKER

The peak power tracker uses the small amount of 120Hz voltage ripple naturally present on the solar array to determine on which part of the IV characteristic the operating point lies. With this information, a suitable error signal can be sent to the input voltage control circuit which will make the inverter move towards the peak power point of the array.

At the 120Hz frequency of the voltage ripple, the array impedance is large compared to that of the 6,000μF input capacitor, a suitable circuit model is shown in Fig. 8.

Fig. 8 Solar Array and Input Filter Model for Peak Power Tracker.

It can be shown that the ac component of \( V \),

\[
\hat{V} = \frac{I_{sol}}{20C} \sin 2\omega t
\]

thus the maximum array voltage always occurs at 45° and 225° of the 60Hz line sine wave and the minimum array voltage at 135° and 315°.

The peak power tracker operates by determining the difference between the array power at the low voltage points of the ripple (135° and 315°) and the power at the high voltage points (45° and 225°).
Fig. 9
Computer Generated Plots of Array IV and PV Characteristics
When $(P_{v_{\text{min}}} - P_{v_{\text{max}}}) > 0 \Rightarrow$ Peak power point lies at a lower voltage.

When $(P_{v_{\text{min}}} - P_{v_{\text{max}}}) < 0 \Rightarrow$ Peak power point lies at a higher voltage.

A computer simulation of the power ripple for various operating points is shown in Fig. 9.

The magnitude of $(P_{v_{\text{min}}} - P_{v_{\text{max}}})$ is an indication of how far away the peak power point is. Thus, this output can be directly used as an input to the array voltage control circuit.

In order to allow the use of low cost components, only the dc component of the array power is computed by the circuit.

\[ \hat{P} \text{ for small signal condition may be approximated by } I \hat{V} + V \hat{I} \]

Note that both multiplications consist of one dc referenced quantity and one ac signal. This allows the use of low cost untrimmed transconductance amplifier for the multiplication. The bias input is used for the dc quantity and the differential input for the ac signal. (Fig. 10) (Input offset voltage does not matter since the input is ac.) However, it is still important that the gains for the two multiplications be identical. In order to achieve this, the same amplifier is multiplexed between the two operations with exactly 50% duty cycle, and its output is low pass filtered to obtain the $\hat{P}$ or power ripple signal. This signal is then fed to two sample and hold circuits, one samples at 45° and 225°, and the other at 135° and 315°. A differential amplifier then computes the difference between the two samples, which is the desired error signal.

**Fig. 10 Peak Power Tracker Block Diagram**

**VII. START UP SEQUENCING**

In the design of the converter input, the goal was to make it as rugged as possible. Although the operating range is from 160 to 240VDC, the inverter can run off an array with an open circuit voltage of up to 400VDC, and will tolerate brief periods up to 600VDC. (The input capacitors are the main limitation, not the semiconductors.)
This ruggedness is achieved without extreme overrating of the buck stage transistors. It is done by simply disabling all switching action when the input voltage exceeds 260V. When the transistors are not switching, the voltage stress on them is reduced by a factor of 2. To enable the converter to start up when powered from a high open circuit voltage array, the array is initially shorted by R1 (Fig. 3). When the relay opens, the converter immediately loads the array so as to prevent it from ever reaching its open circuit voltage. Note that relay R1 does not have to be rated for high voltage dc switching because it is effectively snubbed by the input filter caps and the diode in parallel with R2. Relay R2 always opens before R1 closes, so it only switches about 1 Volt, and can also be quite small. The resistor in parallel with R2 discharges the input capacitors when R1 closes, preparing them for the next turn on. A timing diagram is shown in Fig. 11.

Fig. 11 Sequencing Timing Diagram
In 1981 an investigation of alternate power converter schemes for residential applications was completed at the General Electric Research and Development Center (Report No. SAND81-7031). In that study a high frequency link scheme was recommended for the cases where transformer isolation between the photovoltaic array and the utility was desired. The high frequency link approach offers savings in weight and the potential for future cost reductions compared to the more conventional approaches which employ 60 Hz transformers. An efficiency in the neighborhood of 93% was predicted.

Figure 1 shows a simplified schematic of the scheme under development. A full bridge transistor inverter converts the dc array voltage into high frequency ac (the frequency sweeps between 15 to 25 kHz) which is then transformed and rectified. The transformed dc voltage is then transformed back to 60 Hz ac by the four output transistors. An 8051 single chip microprocessor will control the PCS while additional logic provides the required fast fault sensing and modulation (See Figure 1 for a list of functions performed by the microcomputer).

The microcomputer generates a pure 60 Hz current reference wave which is phase locked with the ac line voltage, \( v_L \). The actual output line current, \( i_L \), is sensed and compared to the reference wave. The switching of the inverter transistors Q1 through Q4 are then controlled to minimize the difference between the commanded and actual line currents. A total harmonic current distortion of less than 5% is predicted with no single harmonic greater than 3%.

Figure 2 shows a rendering of the units under construction while Figure 3 shows an internal view. The unit is estimated to weight 35 pounds.

Under the present contract, we are designing, fabricating, and developing two 4 kW prototype units based on the high frequency link scheme. As of this writing, the detailed design is complete and fabrication of the first unit is approximately 60% complete.
Figure 1. Utility interactive power converter with a high-frequency transformer link.
Figure 2. Conceptual package.
Figure 3. INVERTER FRONT VIEW
(covers removed)
48 Vdc/3kW 100 KHZ Utility Interface PCS

J. Ross, Alpha Energy Systems

(paper not available at time of printing)
60kW, 3Ø SCR/GTO Hybrid PCS

W. Rippel, JPL

(paper not available at time of printing)
PCS PERFORMANCE TESTING
Tom Kay and Ward Bower
Sandia National Laboratories
Albuquerque, NM 87185

An engineering evaluation program has been established for candidate photovoltaic power conditioners. The primary focus of this activity is to characterize photovoltaic power conditioning performance, to identify potential operating problems and to work with the manufacturer in correcting these problems. A unique test facility has been developed at Sandia Laboratories that provides controllable ac and dc interfaces as well as environmental chambers, electromagnetic and acoustical emissions instrumentation, and other equipment required for a complete evaluation of available hardware.

A.C. Measurements Circuit

The steady-state and transient behavior of low-voltage power distribution circuits in utility systems is not well documented. Available information indicates that a wide range of characteristic impedances, voltage regulation profiles, ambient harmonic levels, disturbance magnitudes and durations can be expected. In order to test for this myriad of conditions, Sandia has developed a unique utility line simulator. The system is rated at 480V, 75 kVA, 3-phase and has the capability for 240V, 1-phase.

In addition to conventional motor and diesel generators, the test circuit employs an IEEE STD #387 pulse generator and a 3-phase harmonic generator. The pulse generator produces typical over-voltage transients found in high impedance, low-voltage ac power circuits. Three single-phase coupling transformers are used to introduce harmonics in series between the power conditioner under test and the utility line. It is intended that this harmonic generator will test the effects of power line ambient harmonics, varying source impedance, and voltage phase shift on the power conditioner.

D.C. Measurements Circuit

Thorough inverter performance evaluation requires a controllable and well behaved source of dc power. For photovoltaic inverters the most realistic source is an actual array. Unfortunately, array output is weather dependent and requires a large number of selector switches to provide variability in the I-V characteristics.

A compromise approach has been adopted where array simulators are used to compliment measurements on the PV array. This provides the voltage, current, and power ranges necessary to evaluate the power conditioner under normal and extreme operating conditions.

Two array simulators were developed for this facility. One is rated 10 kW with manual controls for open circuit voltage, short circuit current, and the related slopes which determine fill factor of the I-V curve. A 75 kW simulator is also being used with the same manual controls and an optional automatic computer control. Both simulators provide good control and selection of the I-V characteristic. Since simulators are lumped element devices, their output impedance changes with frequency. Hence, 120 Hz ripple measurements may be invalid and inverters that use ripple detectors to track max-power will not operate properly with these simulators. When used with compatible power conditioning hardware, the simulators are a valuable tool for making threshold, no load-loss, and some efficiency measurements. The data collected must be correlated and normalized, and the complete test circuit must be well understood and documented before valid results can be obtained.

Instrumentation and Procedures

Evaluating the performance of power conditioning subsystems involves a wide range of measurements including varying dc inputs, ac outputs, harmonic distortion, background levels, and other related signals, as well as various environmental conditions. The power conditioners operate on different principles, current sourced versus voltage sourced, for example, and shifts in array or utility characteristics can produce errors which are often instrumentation dependent. Therefore, flexibility must be designed into test set-up, instrumentation, and procedures. Techniques to ensure instrumentation accuracy have been established and are being documented. Calibration/normalization procedures are being used and techniques to cancel effects such as zero reference drift and hysteresis in dc instrumentation are being applied.

Draft procedures for PCS evaluation have been written. These procedures will be reviewed by industry, standards and safety organizations and others to insure a complete and thorough procedure document.

Results of some PCS testing are presented to illustrate measurement technique, source, load, and input-output comparisons.
SANDIA NATIONAL LABORATORIES
POWER CONDITIONING EVALUATION CAPABILITIES

AC CAPABILITIES

• UTILITY GRID SUPPLIED POWER
  1. 480 Volt - 3 Phase Power - 225kVA and 75kVA
  2. 208 Volt - 3 Phase Power - 225kVA and 75kVA
  3. 240 Volt - 1 Phase Power - 50kVA (dry), 35kVA and 10kVA residential

• UTILITY SIMULATOR SOURCES
  1. 125kVA Motor Generator with Phase and Voltage Control
     ±12° Phase Shift Capability
     380 Volt to 520 Volt Adjustability
  2. 75kVA Diesel Engine Generator
     50Hz to 65Hz Frequency Range

• UTILITY LOADS (RESISTIVE AND REACTIVE)
  1. 150kW Resistive Load Adjustable in 1kW Steps
  2. 150kVAR Inductive Load Adjustable in kVAR Steps
  3. Test Fixtures to Produce Temporary Short Circuits

• HARMONIC GENERATOR - 18kW with 6kW per Phase (May 1983)
  1. Microprocessor Controlled to Produce Selectability of Harmonic Content
  2. First Subharmonic to 50th Harmonic of 60Hz

• PULSE GENERATOR - For IEEE 587 Surge Test (April 1983)
  1. 6kV Peak Pulse with 1.2 µsec Rise and 50 µsec Width at Half Amplitude
  2. 3kA Pulse with 8 µsec Rise and 20 µsec Decay to Half Amplitude
  3. 100kHz Oscillatory Damped Waveform with 60Hz Synchronization Control
AC POWER INSTRUMENTATION FOR SINGLE PHASE
PCS EVALUATION TESTS

AUDIO TRANSFORMER

VOLTAGE SENSE

TO SPECTRUM/DISTORTION ANALYZER

CURRENT SHUNT

CTA-113 AC CURRENT AMPS

PC5-32D AC POWER POWER

VT2RV AC VOLTS VOLTS

WH3-32 AC W-HR POWER W-HR PULSE

VOLTS/AMPS

POWER (NOT USED)

AC OUT TO UTILITY
SANDIA NATIONAL LABORATORIES
POWER CONDITIONING EVALUATION CAPABILITIES

DC CAPABILITIES

- PHOTOVOLTAIC ARRAYS (WITH NOMINAL INPUT 1000W/m², CELL TEMPERATURE 25°C)
  1. 2kW Composite Array
     14V to 310V dc Open-circuit in 14V Steps
     10V to 250V dc Nominal Operating in 10V Steps
  2. 10kW Battelle Building Block Array (Completed Dec 82)
     175V to 305V dc Open-circuit in 6V Steps
     125V to 275V dc Nominal Operating in 5V Steps
     2.5kW, 5kW, 7.5kW and 10kW Selectable

- PV ARRAY SIMULATOR
  1. 10kW Simulator - 80 to 280V
     0 to 42A
     Presently being modified for pilot cell operation
  2. 75kW Simulator - 10 to 400V
     0 to 250A
     Can be modularized to 11kW, 22kW etc. to 75kW in
     11kW Steps. Remotely programmable with computer.

- REGULATED, CURRENT LIMITED POWER SUPPLIES
  1. 0 - 10kW Voltage and Current Regulated - 0 to 300V
     0 to 40A
  2. Soft Power Supply for Start-up and Troubleshooting
     0 to 300V Continuously Variable
     0 to 2A with Minimum Surge Capability

- ARRAY AND ARRAY SIMULATOR EVALUATION
  1. Microprocessor Controlled Capacitive I/V Curve Tracer
     0 to 500V
     0 to 30A
  2. Manual Load Stepping (Resistive) for Characterizing Simulators
DC POWER INSTRUMENTATION FOR SINGLE PHASE
PCS EVALUATION TESTS

D.C. IN
FROM
ARRAY

WH7-30
DC W-hr

HI OUT
LO IN
LO OUT
MAGTROL

VOLTS

W-hr
(POWER)
(PULSE)

PCB-5-01
DC POWER

CTA 101
DC CURRENT

CVT

CVT

CVR

VOLTAGE
SENSE

D.C. OUT
TO PCU

(NOT USED)
TEST CIRCUIT BLOCK DIAGRAM
PV/UTILITY INTERFACE ISSUES

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The integration of significant quantities of photovoltaic (PV) arrays into the electric utility grids is dependent upon the electric utilities having sufficient confidence that the PV systems will not have a deleterious effect on the utilities from the standpoint of 1) safety, 2) quality of power and, 3) operational procedures. Should a good confidence level not exist, the utilities will (quite understandably) require connection hardware on residential and intermediate arrays, which does have a high confidence level and which will seriously erode the hoped for cost effectiveness of these systems. The central station sized arrays will have farther reaching impacts including automated generation control and may have a major impact on requirements for such topics as spinning reserve.

It is from this point of view that the Sandia National Laboratories PV program approaches the utility interface questions. Sandia currently has several ongoing contracts which are approaching these questions from both the analytical and experimental points of view. In addition, Sandia is soliciting input from electric utility companies to confirm that the issues we are pursuing are, in fact, the issues they are concerned with. These issues can be grouped under 1) Steady State - those conditions which will exist during normal system operation, 2) Transient - phenomena which occur during the several cycles following a system disturbance, such as clearing of a fault or switching to isolate segments of a system, and 3) Harmonics - problems associated with the power conditioning unit injecting power at frequencies which are integer multiples of 60 Hertz.

The attached vugraphs list major concerns under these various topics along with the organizations which are presently investigating each topic. It will be noticed that in many instances there is more than one organization listed in conjunction with a given topic. If the reader is interested in obtaining information concerning a particular topic, it will be worthwhile contacting each organization listed as he will find that they are all approaching the topic from a different point of view or in a somewhat different manner.
UTILITY INTERFACE ISSUES

- STEADY STATE
- TRANSIENT
- HARMONICS
STEADY STATE

- VOLTAGE PROFILES - UTA, PURDUE, SE RES, SW RES

- OPERATION
  AUTOMATIC GENERATION CONTROL - ASU
  AUTOMATED DISTRIBUTION CONTROL

- SAFETY
  GROUNDING - BECHTEL
  DC ISOLATION - UTA
  UTILITY INTERTIE MODULE

- MAINTENANCE
  ACCESSIBILITY
  DEGRADATION DETECTION
TRANSIENT

- SHORT CIRCUITS

  DETECTION & CLEARING - UTA, BECHTEL,
  SE RES, SW RES

- OPEN CIRCUITS

  ISLANDING - SE RES, SW RES
HARMONICS

- AMBIENT LEVELS
- IMPACT OF PV ON HARMONIC LEVELS
- EFFECT OF HARMONICS

UTA
SE RES
SW RES
The primary objective of this contract was to determine and evaluate the dynamic electrical behavior of representative distribution networks containing various penetrations of dispersed PV power generation. For the purposes of investigation, four power conditioning systems were selected as representative of those being considered or used in PV applications. Two of these systems are single phase arrangements suitable for residential applications (5-10 kW). The other two are representative of power levels of 250 kW to several megawatts. Simplified electrical diagrams of these systems are illustrated in Figure 1.

The first objective was to establish computer representations of each of these systems in a detail sufficient to portray the switching of each valve within the inverter. In the case of the line commutated systems, an analog computer was used with the valves represented using dedicated analog and logic hardware. In the case of the self commutated systems, a hybrid computer was used with the digital computer used to control inverter switching (Figure 2). A detailed discussion of the modeling techniques used to represent the inverters and the control systems that are associated with each of the PV systems is provided in SAND82-7160.

The second objective involved incorporating these models into detailed representations of representative distribution networks. Single phase secondary (Figure 3) and three phase primary (Figure 4) distribution systems were considered. Numerous studies were performed so as to evaluate the dynamic performance of the PV-utility systems. Both steady state and transient conditions were investigated. Transient tests included inverter startup, induction motor (load) switching, feeder tripping and reclosure, feeder faults, etc. The tests were performed under various loading conditions, PV penetrations and different mixes of static and induction motor loads. Representative studies are illustrated in Figures 5-7. Figure 5 illustrates the response of the single phase secondary distribution system following a step increase in insolation from 10 mW/cm² to 100 mW/cm². Figure 6 illustrates the corresponding response of the single phase, self commutated PV system. A representative study involving the three phase primary distribution system is shown in Figure 7 which illustrates the system response following startup of a large 2250 hp induction motor near SCI-2 (Figure 4).

The studies indicate that the dynamic interactions between neighboring single phase PV systems are relatively minor, occurring in systems with a low short-circuit ratio (<5.0). The nature of these interactions is the subject of ongoing research. In the case of the three phase systems, the line and self commutated systems were able to withstand most test disturbances without failure and with relatively short recovery times. Aside from the potential of commutation failure, the LCI systems appeared to be least sensitive to utility disturbances. The sensitivity of the self commutated systems, which is attributed to the use of discrete patterns to continuously regulate a weak source, can likely be reduced through improved inverter control techniques. Present research is focused on experimental verification of the computer models developed as part of this work.
PHOTOVOLTAIC POWER SYSTEM CONFIGURATIONS STUDIED

Figure 1

**PV ARRAY**

- **Converter:**
  - AC System
  - 10 kW
  - 339.4 V (peak)
  - 58.8 A (peak)

- **Series Reactor:**
  - $C_{PF} = 33,000 \mu F$
  - $L_{c} = 0.468 \mu H$
  - $I_{c} = 0.117 \mu A$

- **Filter:**
  - $C_{PF} = 30,000 \mu F$
  - $L_{c} = 0.288 \mu H$
  - $I_{c} = 0.456 \mu A$

- **Output Transformer:**
  - $L_{t} = 0.046 \mu H$

**PV ARRAY**

- **Converter:**
  - AC System
  - 200 kW
  - 892 V
  - 850 A

- **Series Reactor:**
  - $C_{PF} = 60,000 \mu F$
  - $L_{c} = 0.0009 \mu H$
  - $I_{c} = 0.0068 \mu A$

- **Filter:**
  - $L_{c} = 0.046 \mu H$

- **Output Transformer:**
  - $L_{t} = 0.0668 \mu H$

**PV ARRAY**

- **Converter:**
  - AC System
  - 534 kW
  - 892 V
  - 850 A

- **Series Reactor:**
  - $C_{PF} = 33,000 \mu F$
  - $L_{c} = 0.468 \mu H$
  - $I_{c} = 0.11 \mu A$

- **Filter:**
  - $L_{c} = 0.288 \mu H$

- **Output Transformer:**
  - $L_{t} = 0.046 \mu H$
SIMULATION BLOCK DIAGRAM - LINE COMMUTATED SYSTEMS

Figure 2

SIMULATION BLOCK DIAGRAM - SELF COMMUTATED SYSTEMS

ANALOG

DIGITAL

DEFINE AND STORE
SWITCHING PATTERNS
L1(K,J), L4(K,J)

PATTERN INDEX

INV SYNC

READ PATTERN
INDEX

PEAK SYNC
LINE

DETERMINE GATING SIGNAL
L1(K,J), L4(K,J)

NO

YES

133
SECONDARY DISTRIBUTION SYSTEM STUDIED

Figure 3

T1-100' #4/0 Al Triplex
T2-50' #2 Al Triplex
LOADS - 10.5 KVA at 0.95 pF
PRIMARY DISTRIBUTION SYSTEM STUDIED

Figure 4

Feeder 25351

Feeder 25356
SECONDARY SYSTEM RESPONSE FOLLOWING STEP INCREASE IN INSOLATION

Figure 5
SELF COMMUTATED PV SYSTEM RESPONSE FOLLOWING STEP INCREASE IN INSOLATION

Figure 6

\[ v_{ac} \]
\[ \phi_{ac} \]
\[ i_{ac} \]
\[ V_{PVA} \]
\[ P_{PVA} \]
PRIMARY DISTRIBUTION RESPONSE FOLLOWING STARTUP OF 2250 HP INDUCTION MOTOR

Figure 7
EFFECTS OF PV INVERTERS ON DISTRIBUTION FEEDERS

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A study has been conducted to evaluate the effects of the inverters of utility-interactive PV power systems on the distribution feeder. The study was based on a particular distribution feeder and the characteristics of a 6.5 kW utility-interactive PV power system at The University of Texas at Arlington (UTA).

The effect of PV inverter power and reactive power on the voltage regulation of the feeder was evaluated by conducting computer load flow studies. In these studies various percentages of the residences were assumed to have PV power systems with power generation equal to the PV system at UTA. Various inverter power factors were considered. The studies indicated that an inverter power factor of 0.707 or less would result in a reduction in line voltage but an inverter power factor of 0.80 or greater would result in an increase in line voltage. However, for the case of 20% of the homes having PV power systems, the voltage changed by less than 2% from the case of no PV systems and was within specified limits.

The effect of inverter harmonic currents on the feeder line voltage was investigated based on computer simulation of the residences having line commutated inverters with harmonic currents as derived by Landsman (DOE/ET 20279-115). The customer loads were modeled as a combination of resistance loads and single-phase induction motors. Although the studies are not yet complete, preliminary indications are that if 20% of the homes had line commutated PV inverters, the total harmonic distortion from this source would be less than 2%. These results are very sensitive to the modeling of the customer loads.
VOLTAGE PROFILES

DISTANCE FROM S.S.: HUNDREDS OF FEET

BASE CASE S.S. POWER: 6.42 MW
DISTRIBUTED P.V. POWER @ 20% SAT.: 1.49 MW
INDIVIDUAL UNIT P.V. POWER: 4.66 kW
CONNECTED CAP. BANKS: 4.2 MVAR

DISTANCE FROM S.S.: HUNDREDS OF FEET

BASE CASE S.S. POWER: 3.44 MW
DISTRIBUTED P.V. POWER @ 20% SAT.: 0.447 MW
INDIVIDUAL UNIT P.V. POWER: 1.40 kW + 4.66 kVAR
1.40 kW + 2.69 kVAR
1.40 kW + 0.00 kVAR
CONNECTED CAP. BANKS: 0.9 MVAR
Equivalent Circuit of a Single Phase Motor (Capacitor Start).

Impedance of a Single Phase Motor as a Function of Frequency (Capacitor Start).
Equivalent Circuit of a Capacitor Run Single Phase Induction Motor.
Impedance of Main Winding (Capacitor Run)

Impedance of Auxiliary Winding (Capacitor Run)
Total Impedance of a Capacitor Run Motor.

Voltage Profile for Third Harmonic (20% of Homes With PV Systems).
Voltage Profile for Fifth Harmonic (20% of Homes With PV Systems).

Voltage Profile for Nineteenth Harmonic (20% of Homes With PV Systems).
SESSION IV

Session Chairman: Tom Harrison
OVERVIEW OF INTERMEDIATE PV PROGRAMS

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PRDA-35, PRDA-38, Grant and projects assumed from others will be reviewed briefly.

Items to be touched on for each site will be:

1. Location
2. Size
3. Construction complete date
4. Date when data gathering became reliable
5. Date when site got to full automatic status
6. Availability
7. KWH Produced to date
8. Problems

Sites will include: BDM (Albuquerque), Beverly, DFW Airport, Hawaii Hospital, Lovington, El Paso, Oklahoma City, San Bernardino, Phoenix Airport, Mead, Nebraska, Natural Bridges, Bryan, Ohio, Mt. Laguna, MC' (Blytheville), Senatobia and Georgetown, S.M.U.D., Hesperia.
PERFORMANCE OF FLAT-PLATE PHOTOVOLTAIC SYSTEMS

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The system application experiments at the Newman Power Station in El Paso, Texas, and the Lovington Square Shopping Center in Lovington, New Mexico, have been operating successfully for more than two years. The 24-month dc energy production for the Newman Power Station system was 60,620 kilowatt hours; for the Lovington Square Shopping Center system, 375,000 kilowatt hours. Both flat-plate photovoltaic systems produced less the second year than they did the first year. This may be due to several factors and analysis is underway to pinpoint the exact causes.

The DOE-funded operation and maintenance contract will expire in June for both projects. In preparation for this, the responsibility for system operation and maintenance has been transferred from the New Mexico Solar Energy Institute (NMSEI) to the respective utilities. Documentation has been generated and reviewed and some training has been conducted to ensure successful system operation. Results are encouraging and the operating personnel have relied on NMSEI less and less in the past few months.

Total maintenance man-hours have been recorded for both systems. The data acquisition system has required the most attention at each site. Next are the power conditioning units at the Lovington Square Shopping Center, and lastly, the photovoltaic arrays. Few actual hardware failures have occurred and most of the maintenance action has consisted of "resets" of error conditions.

The future plan for both systems is for utility operation unless and until maintenance costs become prohibitive. No systematic data recording will be performed, but some performance data may be available from the operators.

Both of these projects have successfully demonstrated that flat-plate photovoltaic systems are technically viable. The cost remains the major roadblock to widespread utilization of this energy option.
EL PASO PV SYSTEM

PV ARRAY

• 278 M² PANEL AREA
• 168 M² ACTIVE SILICON AREA
• FIXED 26° TILT — DUE SOUTH
• 64 PARALLEL CONNECTED STRINGS
• 9 SERIES CONNECTED MODULES PER STRING
• FIXED VOLTAGE OPERATION — 135 VOLTS
• 150 AMPERES MAXIMUM
NEWMAN POWER STATION PHOTOVOLTAIC PROJECT

System Startup January 27, 1981
22-Month Total = 57 Mwh

ENERGY PRODUCED [Mwh]

MONTHS

16 FEBRUARY 1983

NMSEI
NEWMAN POWER STATION PHOTOVOLTAIC PROJECT

- TOTAL DC ENERGY PRODUCED (12/31/82) 58,889 KWH
- MONTHLY AVERAGE (23 MONTHS) 2,560 KWH
- DAILY AVERAGE (703 DAYS) 83.5 KWH
- SYSTEM AVAILABILITY
  OVERALL 93.0%
  SYSTEM PROBLEMS 95.8%

16 FEBRUARY 1983 NMSEI
NEWMAN POWER STATION PHOTOVOLTAIC PROJECT

MAINTENANCE

67 OCCURRENCES

- ARRAY 26%
- ODAS 61%
- CONTROL 13%

283 MANHOURS

- ARRAY 21%
- ODAS 70%
- CONTROL 9%

DOES NOT INCLUDE SEI SPECIAL TESTING OR TRAVEL TIME
DOES NOT INCLUDE SOLAR POWER COOP FIELD WORK
DOES NOT INCLUDE PONSFORD BROS FIELD WORK
DOES NOT INCLUDE SNL WORK ON TRACKER/ODAS

16 FEBRUARY 1983

NMSEI
THE LOVINGTON 100 KW PV SYSTEM

PV SUBSYSTEM

- 50 KW SUBFIELD
  842 M² MODULE AREA
  490 M² ACTIVE SILICON AREA
  21 SUBARRAYS IN PARALLEL
  80 MODULES
  5P x 16S ELECTRICAL CONNECTION
  220 - 260 VOLTS DC
  230 AMPS MAXIMUM
LOVINGTON SQUARE SHOPPING CENTER PHOTOVOLTAIC PROJECT

System Startup March 17, 1981
19-Month Total = 332 Mwh

16 FEBRUARY 1983
LOVINGTON SQUARE SHOPPING CENTER PHOTOVOLTAIC PROJECT

MAINTENANCE

248 OCCURRENCES

ODAS 46%
PCU 47%
ARRAY 7%

582 MANHOURS

ODAS 41%
ARRAY 39%
PCU 20%

DOES NOT INCLUDE 148 MANHOURS TO CHANGE ARRAY TILT ANGLES
DOES NOT INCLUDE SNL WORK ON TRACKER/ODAS
DOES NOT INCLUDE SOLAR POWER CORP FIELD WORK
DOES NOT INCLUDE WEED CONTROL, VISITOR CENTER MAINTENANCE OR PUBLIC TOURS

16 FEBRUARY 1983
NMSEI
LOVINGTON SQUARE SHOPPING CENTER PHOTOVOLTAIC PROJECT

• TOTAL DC ENERGY PRODUCED (12/31/82) 342,705 KWH
• MONTHLY AVERAGE (19.5 MONTHS) 17,514 KWH
• DAILY AVERAGE (653 DAYS) 525 KWH
• SYSTEM AVAILABILITY 99.9%
• PCU OPERATING HOURS/DAILY AVERAGE
  UNIT A 6013/9.2 HRS
  UNIT B 6193/9.5 HRS

16 FEBRUARY 1983

NMSEI
As a part of the Department of Energy PERDA series of photovoltaic power systems projects, Science Applications, Inc., has designed, installed and tested a nominal 135 kW utility interactive photovoltaic power system located at the Oklahoma Center for Science & Arts, Oklahoma City, Oklahoma. The project evolved in three phases beginning with the analysis/design phase initiated in October 1978. Installation and activation of a resulting nominal 135 kW mirror enhanced design option was completed in February 1982. The power system has since been operational and under test and observation as the third phase entitled test/evaluation.

The PV array is based upon the polycrystalline silicon technology of Solarex Corporation. System modules are composed of a 6 x 12 cell arrangement with complete series/parallel interconnection to provide optimal power capacity and reliability in combination with the enhancement mirrors. As shown below the array is tilted at 30° with the corresponding mirrors angled to the north at 39°. The mirrors provide reflective enhancement from late March through October with peak output occurring in late June.

Electrically two groups of 9 strings, containing 84, 5 volt, 14 amp, modules each, compose the array. By design, at test conditions the array operates at 420 volts, 252 amps and is capable of delivering 105 kW without enhancement and 140 kW with peak enhancement.

The power conditioning system is composed of a Windworks, Inc. 150 kW Gemini, 3 phase, 6 pulse line commutated static power conditioner. The unit operates from 320 VDC to 450 VDC input with a 360 VAC phase to phase output. Isolation and step up to the utility 480 VAC four wire termination are performed with a 180 KVA static drive transformer.

Currently the system is fully operational after experiencing some early break in failures. Two major operational anomalies have surfaced in this first year.
1. A 15% short fall in array peak capacity

2. Power conditioner induced electrical interference with facility sound and lighting equipment

Tests performed on the photovoltaic array during periods of no light enhancement indicate that the array conversion efficiency is down considerably from the design expectations. The shortfall appears to be largely due to poor module performance, unless serious mismatching within the array strings, although highly unlikely, is found to be present when further extensive measurements are completed. Interference from the system power conditioner with high performance audio and special effects lighting has occasionally forced temporary shutdowns of the entire power system. Investigation and preliminary tests indicate the problem is potentially attributable to the presence of the PCUs commutation notch on the OCSA facility electrical system. Power system equipment failures have been chiefly attributable to equipment breakin, and required the system to be shutdown for much of the first few months of operation. The data acquisition system has also accumulated a track record for failures, maintenance and downtime, which has made evaluation of the systems performance innovations difficult. Operation and maintenance has been contained to occasional equipment inspections and instrumentation observation. Due to local climate conditions and nominal air pollution levels, array cleaning will only be necessary once annually.

The system observation/test activities will continue through the spring and early summer of 1983. During this period further investigation will be made into the effects of mirror enhancement, maximum power tracking and the cause of the reduced array capacity. Several equipment implementation/revision tasks directed at improving the data acquisition system and eliminating the power conditioner induced interference problems will be performed. Additionally, consideration is being given to the implementation of an intelligent system monitor/controller, which will provide a power conditioning system nighttime shutdown feature and several other life cycle cost saving functions.
PHOENIX SKY HARBOR AIRPORT
SOLAR PHOTOVOLTAIC CONCENTRATOR PROJECT

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ABSTRACT

This project, one of four concentrator system application experiments sponsored by DOE's PRDA-35 Program, first delivered solar generated electricity in April, 1982. The 225 peak kW array field is comprised of 80 Martin Marietta "first generation" passively cooled tracking arrays, which feed a Power Systems and Controls inverter. The a.c. power output is stepped up to 12.6 kV and fed directly into the APS power grid at the Airport site. The Martin concentrator module design is identical, with minor exceptions, to the hardware supplied to the 350 kW Saudi Arabian Village Project under the SOLERAS Program. Each concentrator uses a Fresnel lens to focus energy (36X) on a 2.25 inch diameter silicon solar cell. A total of 272 lens-cell combinations are mounted onto a pedestal mounted, two-axis tracking array structure. The system was constructed at a cost of approximately four million dollars.

The initial operating experience has been generally favorable, although several problem areas have been identified. The first year's net a.c. energy production is expected to be about 200,000 kWh, about half the amount expected from predictive models. The most frequently occurring operational problems have been in the array tracker drive, inverter control, current-voltage testing, and module assembly subsystems. During the second operating year, the full-time two man operating crew will be removed from the site to see how the system behaves on its own.

Before completion of the DOE funded operation in June, 1984, data regarding array current-voltage performance degradation vs. time, washing cycle frequency, and component replacement frequency, in addition to energy production values, is expected to be recovered to enhance system evaluation.
SKY HARBOR PHOTOVOLTAIC
CONCENTRATOR PROJECT

Presentation to
Fourth Sandia Systems Integration Meeting
April 13, 1983

CONTRACTOR PERSPECTIVE:

- USER Evaluation
- Looking at Bottom-Line, i.e. Capacity Factor
- Interested in System Performance, not Components (how many kWh's per month)
EVALUATION ISSUES:

- Data Reliability
- System Reliability
- Component Reliability (second order)
- Weather Availability
ODAS REPORTING SYSTEM:

- Coordinated Effort Required to Produce Government Performance Report
- Application Specific Nomenclature
- "Site Event" Reporting
- Incorporation of Changes
- Degree of Redundancy With Contractor Reporting
SYSTEM PERFORMANCE:

- Power Output
- Energy Output
- Capacity Factor
- Downtime Events
PROBLEM AREAS:

- Azimuth Drives
- Inverter Controls
- Module Replacements
- Array Power Testing
CURRENT ISSUES:

- Transfer to Unmanned Operation
- Maintenance of Quality Reporting
- Verification of Reliable I-V Curve Testing
- Lens Washing
- Establish System Performance Criteria
KEY RESULTS FOR THE FIRST SIX MONTHS OF OPERATION OF THE LINEAR FRESNEL LENS
PHOTOVOLTAIC AND THERMAL SYSTEM AT THE DALLAS-FORT WORTH AIRPORT

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P.O. Box 226118, Dallas, Texas 75266

The Dallas-Fort Worth (DFW) Airport photovoltaic and thermal (PVT) application experiment has been operational since 21 June 1982. The system was formally dedicated in July, checkout-tested in August, and has performed on a seven-day-per-week basis since 1 September 1982. The collector field (Figure 1) consists of 110 linear Fresnel lens collector modules mounted in eleven independent tracking groups, called ten-collector arrays. The total collector field aperture area is 245 square meters. The arrays are mounted on the roof of the Central Utility Plant at the airport. The collector field's electrical and thermal outputs are used to power lights and to preheat boiler feedwater, respectively, within the plant (Figure 2). To date, data for six full months of operation have been obtained and analyzed, as discussed below.

Figure 3 summarizes the DFW PVT system performance for the first six months of operation. The first column provides the total hours of array operation per month, while the second column provides the total hours of power conditioning unit (PCU) operation per month. The third column summarizes the total direct normal insolation for each month times the collector field aperture area (245 square meters), i.e., the total direct insolation available to the collectors for each month. The fourth column provides the monthly direct-current electrical output of the system, measured at the input side of the PCU, i.e., after all wiring losses. The fifth column provides the monthly electrical efficiency of the system, i.e., the ratio of the values in columns 4 and 3. The sixth column provides the monthly thermal output of the system, measured at the load heat exchanger, i.e., after all piping heat losses. The seventh column provides the monthly system thermal efficiency, i.e., the ratio of the values in columns 6 and 3. The final column provides the monthly total (electrical plus thermal) efficiency for the system. The bottom row of the chart presents these system outputs and efficiencies for the full six-month period. Several important points should be noted from Figure 3: [i] the PCU has had a large amount of down-time, with a six-month availability of only 84%; [ii] the monthly electrical efficiency is strongly dependent on the monthly PCU availability; [iii] the monthly thermal and total efficiencies are relatively constant, despite widely varying levels of insolation, fluid temperature, and ambient temperature over the six-month period; and, most importantly, [iv] the bottom-line efficiencies for the six-month period are very respectable at 6.8% electrical, 38.5% thermal, and 45.2% total.

The actual daily performance measurements for each of the 181 days of operation are shown in the monthly summaries of Figures 4, 5, and 6. These daily performance results have been analyzed to determine the effect of PCU availability on long-term system electrical efficiency, with the results of this analysis shown in Figure 7. This figure shows the six-month system electrical efficiency, if data are considered only for days which had a PCU availability above the minimum value shown on the x-axis. For example, if the minimum PCU availability is selected at 0%, all 181 days of data are considered and the system electrical efficiency is 6.8%, as previously presented. However, if the minimum PCU availability is set at 90%, only 145 days of data are considered and the system electrical efficiency is 7.8%, a full point higher than the previously presented value. We fully expect to achieve 8-9% long-term electrical efficiencies for the system in the future.

To determine if the system is achieving expected performance levels, we have updated our system simulation computer program (Figure 8) to predict what the system electrical and thermal performance should be under actual measured operating conditions. Figures 9 and 10 present a typical whole-day comparison between predicted and measured system performance. Note that the total (electrical plus thermal) output shows excellent analytical/empirical agreement. However, the electrical output alone (Figure 10) is slightly lower than predicted levels in the morning, but close to predicted levels in the afternoon. This aberration is due to an antenna which shades the collector field during the morning, degrading the electrical output of some of the arrays. This antenna is currently being moved. System electrical performance should improve significantly when this antenna move is completed.
MODULE MOUNTED ON ROOFTOP TRACKER

SEALED CELL PACKAGE

FIGURE 1
VARIAN 1000X GaAs MODULE
Figure 2

D/FW AIRPORT PHOTOVOLTAIC EXPERIMENT

BLOCK DIAGRAM OF THE FRESNEL/PHOTOVOLTAIC/PHOTOTHERMAL POWER SYSTEM

ELECTRICAL SYSTEM

SOLAR CONCENTRATOR ARRAY
(245 m² OF LINEAR FRESNEL COLLECTORS)

260 VDC
27 KW

260 VDC

RECTIFIER

TRANSISTORIZED INVERTER

26 KW
480 VAC-3φ

AUTO SWITCH
(DEPENDING ON
UTILITY WATTAGE)

480 VAC
3φ

25 KW LOAD
(UTILITY PLANT
LIGHTING)

1 KW FOR
PUMP &
PARASITICS

135°F (57°C)
1.7 KG/SEC
30% GYCOL.

102°F (39°C)
5 KG/SEC
FROM CONDENSER
(PRIMARY) OR FROM
BOILER MAKE-UP
WATER TANK (SECONDARY)

95°F (35°C)

PUMP

90°F (32°C)

BOILER FEED:
WATER HTX
(140 KW)

102°F (39°C)

TO BOILER

THERMAL SYSTEM

DO10782-49

UTILITY POWER
480 VAC-3φ

25 KW LOAD
(UTILITY PLANT
LIGHTING)
### Figure 3

**DFW PVT SYSTEM PERFORMANCE SUMMARY**

September 82 thru February 83

<table>
<thead>
<tr>
<th>MONTH</th>
<th>ARRAY OPERATION (HOURS)</th>
<th>PCU OPERATION (HOURS)</th>
<th>AVAILABLE* DIRECT NORMAL INSOLATION (KWH)</th>
<th>ARRAY DC OUTPUT (KWH)</th>
<th>ARRAY ELECTRICAL EFFICIENCY (%)</th>
<th>ARRAY THERMAL OUTPUT (KWH)</th>
<th>ARRAY THERMAL EFFICIENCY (%)</th>
<th>MONTHLY TOTAL EFFICIENCY (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>269</td>
<td>243</td>
<td>39,332</td>
<td>2,949</td>
<td>7.5</td>
<td>15,679</td>
<td>39.9</td>
<td>47.4</td>
</tr>
<tr>
<td>October</td>
<td>199</td>
<td>179</td>
<td>29,226</td>
<td>2,024</td>
<td>6.9</td>
<td>11,698</td>
<td>40.0</td>
<td>46.9</td>
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<tr>
<td>November</td>
<td>131</td>
<td>128</td>
<td>18,549</td>
<td>1,489</td>
<td>8.0</td>
<td>6,935</td>
<td>37.4</td>
<td>45.4</td>
</tr>
<tr>
<td>December</td>
<td>159</td>
<td>124</td>
<td>24,330</td>
<td>1,347</td>
<td>5.5</td>
<td>8,634</td>
<td>35.5</td>
<td>41.0</td>
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<tr>
<td>January</td>
<td>116</td>
<td>101</td>
<td>18,611</td>
<td>1,257</td>
<td>6.8</td>
<td>7,082</td>
<td>38.1</td>
<td>44.9</td>
</tr>
<tr>
<td>February</td>
<td>140</td>
<td>74</td>
<td>19,618</td>
<td>1,040</td>
<td>5.3</td>
<td>7,527</td>
<td>38.4</td>
<td>43.7</td>
</tr>
</tbody>
</table>

**TOTAL**  
1,014  849  149,666  10,106  6.8%  57,555  38.5%  45.2%

*DAILY TOTAL DIRECT NORMAL INSOLATION TIMES ARRAY APERTURE AREA (245m²)*
'Ii
:ell

Figure 4

DFW PVT SYSTEM PERFORMANCE SUMMARY

E-SVSTEMS
Energy Technology Center

OCTOBER. 1982

SEPTEMBER. 1982

DAY

I-'
-.;]

0

ARRAY
OPERATION
(HOURS)

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
WHOLE
MUNTH

PCU
OPERATION
(HOURS)

AVAILABLE*
DIRECT NORMAL
INSOLATION
(KWH)

ARRAY OC
OUTPUT
(KWH)

10.5
9.0
9.0
10.5
10.5
10.5
10.5
9.5
10.3
10.5
10.3
9.0
5.5
10.2
7.8
7.5
10.3
8.5
2.0
8.5
10.2
10.0
10.0
3.5
10.0
8.5
10.0
8.0
10.0
8.5

10.3
6.0
8.7
10.5
8.5
10.3
10.4
9.2
10.2
10.3
5.1
5.2
3.1
9.4
6.0
6.0
9.7
7.3
1.5
8.5
10.2
10.0
10.0
3.5
9.5
8.0
9.4
8.0
10.0
8.5

1531
942
1402
2266
1547
2083
1699
1384
1479
1726
1608
759
197
1324
486
918
1747
1382
208
1552
2139
2085
1992
198
1752
671
1244
935
782
1274

121.4
55.4
107.2
169.8
97.1
144.6
134.2
106.0
118.5
132.9
46.4
51.6
8.8
95.4
24.0
73.4
131.8
115.3
9.5
134.2
167.3
156.8
162.2
9.3
144.9
44.9
115.7
87.9
64.1
118.0

269.1

243.3

39,332

2948.6

WHOLE MONTH TOTAL EFFICIENCY

ARRAY
ELECTRICAL
EFFICIENCY
(%)

7.9
5.9
7.6
7.5
6.3
'6.9
7.9
7.7
8.0
7.7
2.9
6.8
4.5
7.2
4.9
8.0
7.5
8.3
4.6
8.6
7.8
7.5
8.1
4.7
8.3
6.7
9.3
9.2
8.2
9.3

7.5%
~

ARRAY
THERMAL
OUTPUT
(KWH)

610
386
574
864
570
751
672
552
586
684
628
300
66
557
203
385
706
583
86
663
824
807
801
36
684
186
560
440
333
582

15,679

ARRAY
THERMAL
EFFICIENCY
(%)

DAY

39.8
41.0
40.9
38.1
36.9
36.1
39.6
39.9
39.6
39.6
39.1
39.5
33.5
42.1
41.8
41.9
40.4
42.2
41.3
42.7
38.5
38.7
40.2
18.2
39.0
27.7
45.0
46.1
42.6
45.6

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31

39.9%

WHOLE
MONTH

ARRAY
OPERATION
(HOURS)

PCU
OPERATION
(HOURS)

7.5
9.8
6.3
9.2
9.2
6.5
3.5
4.7
8.8
8.5
4.3

7.0
3.8
6.3
9.1
9.2
6.0
3.5
2.5
8.8
8.5
4.3

7.7
10.0
9.0
9.5
8.0
7.0
8.7
2.8

7.7
5.3
9.0
9.5
6.5
7.0
8.7
2.8

9.2
9.5
9.5
7.7
0
0
9.2
4.3
9.0

9.2
6.0
9.5
7.7
0
0
8.2
4.3
9.0

199.4

179.4

AVAILABLE*
DIRECT NORMAL
INSOLATION
(KWH)

476
1711
838
1152
1118
579
214
237
1499
1200
1090
O. . ercast
1740
1754
1495
1567
981
1324
598
1251
Overcast
Overcast
1320
1693
1048
1438
297
290
1617
322
377

29,226

ARRAY DC
OUTPUT
(KWH)

ARRAY
THERMAL
OUTPUT
(KWH)

ARRAY
THERMAL
EFFICIENCY
(%)

32.2
47.3
74.1
103.8
99.2
51.3
20.7
7.5
130.5
102.0
56.6

6.8
2.8
8.8
9.9
8.9
8.9
9.7
3.2
8.7
8.5
5.2

187
753
387
535
504
284
108
126
641
472
268

39.3
44.0
46.4
46.4
45.1
49.0
50.5
53.0
42.7
39.3
24.6

102.7
64.9
132.5
145.6
81.2
108.9
53.6
23.9

5.9
3.7
8.9
9.3
8.3
8.1
9.0
1.9

572
849
673
704
494
514
271
84

32.9
48.4
45.0
44.9
50.4
38.3
45.3
6.7

121.1
89.8
91.1
106.4
0
0
117 .1
29.7
30.4

9.2
5.3
8.7
7.4

567
786
422
520
0
0
676
145
156

43.0
46.4
40.3
36.2

7.2
9.2
8.1

2,024.1

WHOLE MONTH TOTAL EFFICIENCY

47.4%

ARRAY
ELECTRICAL
EFFICIENCY
(%)

6.9%
~

11 ,698

41.8
45.0
41.4

40.0%

46.9%

'OAIL Y TOTAL DIRECT NORMAL INSOLATION TIMES ARRAY APERTURE AREA (245m 2 )

'DAILY TOTAL DIRECT NORMAL INSOLATION TIMES ARRAY APERTURE AREA (245m 2 )

OS030783·124

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•

•

•

•

•

•

•

•

•

•


# DFW PVT System Performance Summary

## November, 1982

<table>
<thead>
<tr>
<th>Day</th>
<th>Array Operation (Hours)</th>
<th>PCU Operation (Hours)</th>
<th>Available* Direct Normal Insolation (KWh)</th>
<th>Array DC Output (KWh)</th>
<th>Array DC Electrical Efficiency (%)</th>
<th>Array Thermal Efficiency ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.3</td>
<td>4.3</td>
<td>254</td>
<td>18.5</td>
<td>7.3</td>
<td>90</td>
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<td>2</td>
<td>4.3</td>
<td>4.3</td>
<td>18</td>
<td>6.6</td>
<td>8.8</td>
<td>37.6</td>
</tr>
<tr>
<td>3</td>
<td>8.2</td>
<td>8.2</td>
<td>1141</td>
<td>90.0</td>
<td>8.6</td>
<td>441</td>
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<td>9.2</td>
<td>9.2</td>
<td>1572</td>
<td>133.9</td>
<td>8.5</td>
<td>575</td>
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<tr>
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<td>9.2</td>
<td>9.2</td>
<td>1691</td>
<td>138.1</td>
<td>8.5</td>
<td>647</td>
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<tr>
<td>6</td>
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<td>9.0</td>
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<td>415</td>
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<tr>
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<td>121</td>
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<tr>
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<td>8.0</td>
<td>99</td>
<td>52.5</td>
<td>8.8</td>
<td>237</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<tr>
<td>12</td>
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<td>8.0</td>
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<td>0</td>
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<tr>
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<td>8.0</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Whole Month

- Total Direct Normal Insolation: 18,549 KWh
- Total Array Aperture Area: 245 m²
- Total Electrical Efficiency: 41.4%
- Total Thermal Efficiency: 45.4%

## December, 1982

<table>
<thead>
<tr>
<th>Day</th>
<th>Array Operation (Hours)</th>
<th>PCU Operation (Hours)</th>
<th>Available* Direct Normal Insolation (KWh)</th>
<th>Array DC Output (KWh)</th>
<th>Array DC Electrical Efficiency (%)</th>
<th>Array Thermal Efficiency ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>1.0</td>
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<td>0.0</td>
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<td>-</td>
</tr>
<tr>
<td>3</td>
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<td>5.3</td>
<td>663</td>
<td>56.2</td>
<td>8.5</td>
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<td>8.7</td>
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<td>116.0</td>
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<td>592</td>
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<tr>
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<td>5.3</td>
<td>572</td>
<td>PCU Down</td>
<td>-</td>
<td>223</td>
</tr>
<tr>
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<td>Overcast</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>0.0</td>
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<td>6.5</td>
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<td>-</td>
<td>521</td>
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<td>6.5</td>
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<td>-</td>
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<td>8.3</td>
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<td>-</td>
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<td>1348</td>
<td>105.5</td>
<td>6.7</td>
<td>555</td>
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<tr>
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<td>8.5</td>
<td>1083</td>
<td>81.3</td>
<td>7.5</td>
<td>352</td>
</tr>
<tr>
<td>18</td>
<td>7.3</td>
<td>5.5</td>
<td>993</td>
<td>52.9</td>
<td>5.3</td>
<td>331</td>
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<tr>
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<td>8.3</td>
<td>1451</td>
<td>106.0</td>
<td>7.3</td>
<td>517</td>
</tr>
<tr>
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<td>8.3</td>
<td>1437</td>
<td>110.3</td>
<td>7.6</td>
<td>583</td>
</tr>
<tr>
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<td>6.0</td>
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### Whole Month

- Total Direct Normal Insolation: 1,347 KWh
- Total Array Aperture Area: 245 m²
- Total Electrical Efficiency: 41.0%
- Total Thermal Efficiency: 35.5%

---

*Daily Total Direct Normal Insolation Times Array Aperture Area (245 m²)*

---

DSO29783-123
### JANUARY, 1983

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**WHOLE MONTH TOTAL EFFICIENCY = 44.9%**

*Daily Total Direct Normal Insolation Times Array Aperture Area (245 m²)*

### FEBRUARY, 1983

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**WHOLE MONTH TOTAL EFFICIENCY = 43.7%**

*Daily Total Direct Normal Insolation Times Array Aperture Area (245 m²)*
DFW PVT SYSTEM PERFORMANCE FROM 1 SEPTEMBER 1982 THROUGH 28 FEBRUARY 1983 SHOWING THE EFFECT OF PCU AVAILABILITY
**DFW PVT COLLECTOR FIELD PERFORMANCE SIMULATION**

**INPUT MEASURED TIME, I_{dm}, T_f, T_R EVERY 30 MINUTES**

- \( \eta_{\text{module electrical}} = f \left( T_f, I_{dm} \right) \) FROM PROTOTYPE MEASUREMENTS
- \( F_{\text{longitudinal incidence}} = f \left( \rho_{\text{inc}} \right) \) FROM PROTOTYPE MEASUREMENTS
- \( F_{\text{module-to-module shading}} = f \left( \text{roll angle/aperture shading} \right) \)
- \( F_{\text{row-to-row shading}} = f \left( \text{cell shading/diode closures for seven shaded arrays} \right) \)
- \( F_{\text{wiring/mismatch}} = 0.95 \)

- \( \eta_{\text{field electrical}} = \left( \frac{\eta_{\text{module electrical}} \times F_{\text{longitudinal incidence}} \times F_{\text{module-to-module shading}} \times F_{\text{wiring/mismatch}}}{11} \right) \times \left( \frac{A + \frac{7}{11} F_{\text{row-to-row shading}}}{11} \right) \)

**TOTAL (ELECTRICAL + THERMAL EFFICIENCY)**

- \( \eta_{\text{module full}} = f \left( T_f, T_{dm}, I_{dm} \right) \) FROM PROTOTYPE MEASUREMENTS
- \( F_{\text{longitudinal incidence}} = f \left( \text{end plate shading/cos } \rho_{\text{inc}} \right) \)
- \( F_{\text{module-to-module shading}} = f \left( \text{roll angle/aperture shading} \right) \)
- \( F_{\text{row-to-row shading}} = f \left( \text{aperture shading for seven shaded arrays} \right) \)
- \( F_{\text{heat up/cool down}} = f \left( T_f, T_{dm}, m_{\text{CPsystem}} \right) \)
- \( F_{\text{pipeing heat loss}} = f \left( T_f, T_{dm}, \text{insulation} \frac{k}{\text{D} \cdot \text{L}} \right) \)

- \( \eta_{\text{field total}} = \left( \frac{\eta_{\text{module full}} \times F_{\text{longitudinal incidence}} \times F_{\text{module-to-module shading}} \times F_{\text{heat up/cool down}} \times F_{\text{pipeing/heat loss}}}{11} \right) \times \left( \frac{A + \frac{7}{11} F_{\text{row-to-row shading}}}{11} \right) \)
DFW PVT SYSTEM PERFORMANCE FOR
21 NOVEMBER 1982 - MEASURED
VERSUS SIMULATED TOTAL AND
ELECTRICAL OUTPUTS

DIRECT NORMAL INSOLATION
WHOLE DAY TOTAL = 5626 W-H/M²

TOTAL ENERGY OUTPUT
(ELECTRICAL PLUS THERMAL)
WHOLE DAY TOTAL
CALCULATED 3072 W-H/M²
MEASURED 3059 W-H/M²

ELECTRICAL ENERGY OUTPUT
WHOLE DAY TOTAL
CALCULATED 557 W-H/M²
MEASURED 504 W-H/M²

DIRECT NORMAL INSOLATION
ANTENNA SHADING
WHOLE DAY TOTAL = 5626 W-H/M²
DFW PVT SYSTEM PERFORMANCE
FOR 21 NOVEMBER 1982 - MEASURED
VERSUS SIMULATED ELECTRICAL OUTPUT

Figure 10

ELECTRICAL ENERGY OUTPUT

- CALCULATED
- MEASURED

WHOLE DAY TOTAL
557 W-H/M²

504 W-H/M²

ANTENNA SHADING

DC ELECTRICAL OUTPUT (W/M²)

150
100
50
0

HOURS FROM SOLAR NOON

5 4 3 2 1 0 1 2 3 4 5

DS121682-27
ARCO SOLAR 1Mw LUCO FACILITY

L. A. Schaffer, Arco Solar

(paper not available at time of printing)
FIELD PERFORMANCE ASSESSMENT
OF INTERMEDIATE PHOTOVOLTAIC ARRAYS

Martin K. Fuentes
Sandia National Laboratories
Albuquerque, New Mexico 87185

Over the past few years, the U.S. Department of Energy has installed several intermediate-sized photovoltaic (PV) systems as initial experiments for assessing the performance of various PV system designs. Most of these experiments have now been operational for over a year. Data from each of these sites have been collected at one minute intervals, averaged over ten-minute intervals, and archived at a data reduction center operated for the Department of Energy by Boeing. This presentation describes the analysis on this data to assess the actual performance of the various intermediate systems.

An equation for the array power was formulated to compare the rated performance with the actual performance of each site. The form of the array power equation is as follows:

$$P_{dc} = -A_1 + A_2E + A_3T_c - A_4E\cdot T_c$$

where:
- $P_{dc}$ = DC power
- $E$ = Insolation
- $T_c$ = Cell temperature
- $A_1, A_2, A_3, A_4$ = Coefficients

This equation was applied to each site and to each month of operation, and accurate results were obtained for the Beverly, El Paso, Lovington, and San Bernardino sites. For these sites, with the exception of San Bernardino, it was also possible to track the degradation of the PV array.

In addition, a power equation for the power conditioning subsystem (PCU) was formulated and applied to each site to every month that data was collected. The PCU power equation has the following form:

$$P_{ac} = \text{EFF}_1 \cdot (P_{dc} - P_{th})$$

where:
- $P_{ac}$ = AC power
- $P_{dc}$ = DC power
- $P_{th}$ = Threshold power of the PCU
- $\text{EFF}_1$ = PCU efficiency when the DC power is infinite

Accurate results were obtained for the Beverly, Lovington, San Bernardino, Phoenix, and Blytheville sites. Using this equation, it was possible to compare the PCUs at the different sites, and also track the seasonal variation of the PCU's performance.
SESSION V

Session Chairman: Kent Biringer
THE DOE PHOTOVOLTAIC RESIDENTIAL PROJECT

K. L. Biringer
Sandia National Laboratories
Albuquerque, NM 87185

The DOE Photovoltaic Residential Project is tasked with coordinating the systems analysis, component development and system experiments efforts related to grid-connected PV residences. Sandia National Laboratories has the role of lead laboratory in this project effort with the Albuquerque Operations Office serving as the lead field office for the DOE.

The residential project has been changing to reflect the greater research and technology emphasis of the DOE PV Program. A five-year residential plan has been prepared which reflects this new program direction. The highlights and major milestones of this plan will be presented. In addition, facilities currently in operation will be described along with the key areas of experiment and analysis planned for 1983.
PV RESIDENTIAL PROJECT OVERVIEW

K. L. BIRINGER
SANDIA NATIONAL LABORATORIES
ALBUQUERQUE, NM  87185

PRESENTED AT FOURTH PHOTOVOLTAIC SYSTEMS
AND APPLICATIONS PIM

APRIL 14, 1983
PHOTOVOLTAIC
RESIDENTIAL PROJECT OBJECTIVE

TO ADVANCE THE DEVELOPMENT AND SCIENTIFIC UNDERSTANDING OF SMALL ROOF MOUNTED PV SYSTEM TECHNOLOGY AS A SIGNIFICANT RENEWABLE ELECTRIC ENERGY OPTION FOR THE UNITED STATES.

THE RESIDENTIAL PROJECT WILL EMPHASIZE ESTABLISHING A TECHNOLOGY BASE NEEDED TO PERMIT MEANINGFUL RISK ASSESSMENT BY PRIVATE FIRMS FOR INTRODUCING THE GRID-CONNECTED PV OPTION INTO THE ENERGY SUPPLY MIX.
ELEMENTS OF THE RESIDENTIAL PROJECT

SYSTEMS R&D - TO DEVELOP AND DOCUMENT A DETAILED UNDERSTANDING OF RESIDENTIAL PV SYSTEM DESIGN AND PERFORMANCE TRADEOFFS, UTILITY INTERACTION SAFETY AND RELIABILITY.

ARRAY SUBSYSTEM R&D - TO DEVELOP AND EVALUATE EFFICIENT, RELIABLE AND SAFE PV ARRAY SUBSYSTEMS FOR USE IN RESIDENTIAL SYSTEMS.

POWER CONDITIONING SUBSYSTEM R&D - TO DEVELOP AND EVALUATE EFFICIENT, RELIABLE AND SAFE POWER CONDITIONING SUBSYSTEMS FOR USE IN RESIDENTIAL SYSTEMS.

SYSTEM EXPERIMENTS - TO EVALUATE RESIDENTIAL PV SYSTEM DESIGNS, INTERFACES AND COMPONENTS IN REALISTIC CONFIGURATIONS AND ENVIRONMENTS.
HOW THE RESIDENTIAL PROJECT HAS CHANGED

**WAS**

- Based on market emphasis
- Based on fixed configuration prototypes
- Fully DOE supported
- Fielding DOE funded occupied PV residences

**IS NOW**

- Based on technology emphasis
- Adding concept of flexible prototypes
- Seeking cost sharing agreements
- Monitoring privately funded PV residences
THE PV RESIDENTIAL PLAN

- A DRAFT 5-YEAR RESIDENTIAL PROJECT PLAN HAS BEEN PREPARED

- COMMENTS ON THE PLAN ARE BEING INCORPORATED

- THE PLAN IS STRUCTURED TO RESULT IN AN ESTABLISHED TECHNOLOGY BASE FOR RESIDENTIAL PV

- MAJOR MILESTONES HAVE BEEN IDENTIFIED
## FIGURE 1 - DOE PV RESIDENTIAL PROJECT

<table>
<thead>
<tr>
<th>ACTIVITY</th>
<th>SYSTEMS R&amp;D</th>
<th>ARRAY SUBSYSTEM R&amp;D</th>
<th>PCS R&amp;D</th>
<th>SYSTEM EXPERIMENTS</th>
<th>RES OPERATION</th>
<th>RES TESTING</th>
<th>OTHER EXPERIMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Topical Reports</td>
<td>Block V Modules</td>
<td>Topical Reports</td>
<td>Testing</td>
<td>Block V Modules</td>
<td>Component Tests &amp; Utility Experiments</td>
<td>Multi House Experiment</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- **O** - Begin Activity
- **△** - Milestone
- **△** - Completed Milestone
- **□** - End Activity
- **---** - Current Progress

### Notes:
- DOE PCS Development Complete
- Significant Private Support Started
- Reduced DOE Funding
- DOE Utility Experiments
- End DOE Testing
- PV Residence Operation

**12/12/82**
RESIDENTIAL PROGRAM
ORGANIZATION STRUCTURE

Figure 1
## RESIDENTIAL PROJECT
### SYSTEM EXPERIMENTS STATUS

<table>
<thead>
<tr>
<th></th>
<th>PROTOTYPES</th>
<th>FLEXIBLE PROTOTYPES</th>
<th>FIELD SITES</th>
</tr>
</thead>
<tbody>
<tr>
<td>NORtheast RES</td>
<td>5 OPERATING</td>
<td>3 PLANNED</td>
<td>2 OPERATING (CARLISLE, NORFOLK)</td>
</tr>
<tr>
<td>Southwest RES</td>
<td>8 OPERATING</td>
<td>1-3 PLANNED</td>
<td>2 OPERATING (SANTA FE, YUMA)</td>
</tr>
<tr>
<td></td>
<td>1 DESIGNED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southeast RES</td>
<td>3 DESIGNED</td>
<td>1 OPERATING</td>
<td>3 OPERATING (FSEC, TYNDALL, FUTURE ONE)</td>
</tr>
<tr>
<td></td>
<td>2 PLANNED</td>
<td></td>
<td>4 PLANNED (TVA)</td>
</tr>
<tr>
<td>Hawaii Natural Energy Institute Project</td>
<td></td>
<td></td>
<td>3 OPERATING</td>
</tr>
</tbody>
</table>
ANTICIPATED 1983 HIGHLIGHTS

- IMPROVED UNDERSTANDING OF ARRAY TEMPERATURE CHARACTERISTICS
- SIGNIFICANT TEST DATA AND ANALYSIS ON HARMONICS AND OTHER GRID INTERFACE ISSUES
- CONSTRUCTION OF THREE SE RES PROTOTYPES
- IMPLEMENTATION OF FLEXIBLE TEST BEDS AT NE AND SW RES
- CONSTRUCTION OF RIBBON MODULE PROTOTYPE AT THE SW RES
- EVALUATION OF NEW MODULES
- EVALUATION OF SEVERAL NEW RESIDENTIAL PCS UNITS
- PUBLICATION OF RESIDENTIAL TOPICAL REPORTS
Abstract

DEVELOPMENT OF THE SOUTHEAST RESIDENTIAL EXPERIMENT STATION*
by
Gerard G. Ventre, FSEC
Gobind H. Atmaram, FSEC
Larry E. Banta, GIT

The Photovoltaic Southeast Residential Experiment Station (SE RES) is jointly operated by the Florida Solar Energy Center (FSEC) and the Georgia Institute of Technology (GIT). Cooperating with FSEC and GIT on the project are the Alabama Solar Energy Center and major southeastern utilities including Alabama Power Company, Florida Electric Power Coordinating Group, Florida Power and Light Company, Florida Power Corporation, Georgia Power Company, Jacksonville Electric Authority, Southern Company Services, Inc., Tampa Electric Company and the Tennessee Valley Authority.

The major experiments for which FSEC is responsible include prototype testing, subsystem testing and continued operation of the FSEC PV-house. FSEC is currently designing three prototype systems with 3 to 4.4 kWp arrays using single-crystal Czochalski, polycrystalline and EFG ribbon cells. One standoff and two integral mounting configurations will be utilized. FSEC will act as general contractor for construction of the three prototypes which are scheduled for completion in Fall 1983.

FSEC's flexible subsystem test facility is nearing completion and should be operational in May 1983. It is designed for short-term testing of systems and components; accommodates a large variety of module sizes; and is capable of simultaneous testing of both fixed and tracking arrays.

The FSEC PV-house was recalibrated in February 1983 and over two years of operational data have been reported.

The Georgia Institute of Technology Engineering Experiment Station is responsible for the establishment and operation of a data acquisition and reporting network for the nine PV "field sites." Meteorological and PV system performance data from each of the field sites is fed to Georgia Tech in a variety of formats from the data logging systems used by the various field site operators. Georgia Tech reorganizes and analyzes the data and produces monthly reports for each field site in a uniform data format. Field site data is then archived at Georgia Tech.

The second major area of responsibility for GIT is the design, direction, and analysis of utility interface experiments. A series of experiments will be carried out at the various field sites and at FSEC to investigate problems involving fault protection, harmonic injection and propagation, islanding, voltage regulation/reactive power compensation, and utility operations issues. Georgia Tech will play the lead role in the design and analysis of the experiments, with the experiment construction and performance to be handled by field site and/or utility personnel.

*This project is funded by the U.S. Department of Energy.
FSEC Tasks

1. Develop research plan
2. Design, construct and instrument prototypes
3. Collect data
   — Prototypes
   — Subsystem test bed
   — FSEC PV house
4. Improve residential building design
5. Analyze data, evaluate system performance and reliability
6. Transfer technology to user sectors
7. Convene consulting committee
8. Report status and results
Summary of Prototype Systems

- 5 new prototypes to be constructed at FSEC
- 3 in 1983
- 2 in 1984

Construction of 1983 Prototype Systems

1. FSEC will act as architect, system designer and general contractor
2. Outside firms will review designs
3. Operational in October, 1983
## Summary of Prototype Systems

<table>
<thead>
<tr>
<th>Prototypes (1983)</th>
<th>Array Mounting</th>
<th>Approx. Array Area</th>
<th>Cell/Module Type</th>
<th>Rated Output (at NOCT)</th>
<th>Power Conditioner</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Stand-off</td>
<td>37 m²</td>
<td>Single crystal Cz Photowatt 7050</td>
<td>3 KwP</td>
<td>Solar inverter (Alpha Energy)</td>
</tr>
<tr>
<td>2</td>
<td>Integral</td>
<td>59 m²</td>
<td>Polycrystalline-Solarex PL120</td>
<td>4.4 KwP</td>
<td>Sunverter (Abacus Control)</td>
</tr>
<tr>
<td>3</td>
<td>Integral</td>
<td>58 m²</td>
<td>Ribbon Mobil Ra 180</td>
<td>4.4 KwP</td>
<td>Sunshine 4000 (American Power Conversion)</td>
</tr>
</tbody>
</table>
Schematic Diagram of Prototype System Instrumentation
Experiments at Subsystem Test Bed

- Simulation of utility extreme conditions
- Evaluation of power conditioners (Advanced, experimental and small 1 kw — 4 kw)
- Operation of adjustable tilt and/or tracking array
- Evaluation of advanced technology modules
Electrical Schematic of Subsystem Test Facility
## Two Year Performance Summary of FSEC PV Residence

<table>
<thead>
<tr>
<th>Month</th>
<th>Irradiance incident upon array field measured (kWh)</th>
<th>Array DC output (kWh)</th>
<th>System AC output (kWh)</th>
<th>Array Efficiency</th>
<th>System Efficiency</th>
<th>System Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>8775</td>
<td>8452</td>
<td>N/A</td>
<td>682</td>
<td>627</td>
<td>562</td>
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<tr>
<td>Feb.</td>
<td>7800</td>
<td>7976</td>
<td>N/A</td>
<td>635</td>
<td>530</td>
<td>516</td>
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<tr>
<td>Mar.</td>
<td>10664</td>
<td>10899</td>
<td>N/A</td>
<td>812</td>
<td>695</td>
<td>676</td>
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<tr>
<td>Apr.</td>
<td>11989</td>
<td>9960</td>
<td>914</td>
<td>716</td>
<td>788</td>
<td>620</td>
</tr>
<tr>
<td>May</td>
<td>12732</td>
<td>11754</td>
<td>900</td>
<td>840</td>
<td>776</td>
<td>688</td>
</tr>
<tr>
<td>June</td>
<td>12120</td>
<td>8941*</td>
<td>883</td>
<td>583</td>
<td>746</td>
<td>519</td>
</tr>
<tr>
<td>July</td>
<td>11594</td>
<td>11116*</td>
<td>837</td>
<td>759</td>
<td>721</td>
<td>664</td>
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<tr>
<td>Aug.</td>
<td>10289</td>
<td>11387</td>
<td>759</td>
<td>789</td>
<td>653</td>
<td>687</td>
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<tr>
<td>Sep.</td>
<td>10508</td>
<td>9305</td>
<td>775</td>
<td>644</td>
<td>654</td>
<td>559</td>
</tr>
<tr>
<td>Oct.</td>
<td>10526</td>
<td>8869*</td>
<td>775</td>
<td>648</td>
<td>655</td>
<td>559</td>
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<tr>
<td>Nov.</td>
<td>9656</td>
<td>7337</td>
<td>772</td>
<td>566</td>
<td>637</td>
<td>482</td>
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<tr>
<td>Dec.</td>
<td>8582</td>
<td>7316</td>
<td>687</td>
<td>595</td>
<td>530</td>
<td>506</td>
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<table>
<thead>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Total Irradiance (kWh)</td>
<td>125235</td>
<td>113312*</td>
<td>Average Array Efficiency (for 12 mths)</td>
<td>7.5</td>
<td>7.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Array DC output (kWh)</td>
<td>7302</td>
<td>8269</td>
<td>System Average Efficiency (for 12 mths)</td>
<td>6.4</td>
<td>6.2</td>
<td></td>
<td></td>
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<tr>
<td>Total System AC output (kWh)</td>
<td>8012</td>
<td>7038</td>
<td>System Capacity Factor (for 12 mths)</td>
<td>0.22</td>
<td>0.19</td>
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</table>

*Corrected for irradiance lost due to 'system shutdowns.' Array Area = 62.5 m²
At the Northeast Residential Experiment Station, five roof-mounted, utility-interactive prototype photovoltaic (PV) systems have been designed, constructed and evaluated. Results of two years of normal operation and several special experiments are presented.

The PV systems have operated reliably and predictably. Problems of unreliability in an early power conditioner unit (PCU) have been eliminated. Since mid-1982 there has been a selection of PCUs available with satisfactory operating characteristics. One remaining problem results from the utility service to the NE RES, which suffers regular abnormalities in both voltage and frequency. A PCU sensitive to these parameters (to preclude feeding a "dead" feeder) has on occasion turned itself off, and was then unable to restart due to an array voltage outside of its operating window.

Annual PV generation has been predictable to within 5% using Boston TMY data. The data monitoring system at the NE RES agrees, to within 4%, to the conventional kilowatt-hour meters. On an annual basis, typical monitored residences use from 100% to 250% of the energy produced from the NE RES PV systems. The Carlisle House uses three times the electric energy it produces, on an annual basis. Most of the energy goes into heating the house in the winter. Calculation of the energy exchange between a photovoltaic residence and the utility involves a subtle problem. If the house load is not sampled at a rapid enough rate, the energy flows to and from the utility will be underestimated. The magnitude of the error depends on the nature of the daytime loads.

Array temperatures vary considerably, with direct mount operating hottest, then stand-off, and integral coolest. The General Electric shingle array has suffered considerable degradation. Its normalized maximum power has fallen 30% in the past year. Module temperature within an integral array has been seen to vary by as much as 28 Celsius degrees from one point to another. Modifications were made to the array which reduced this variation, but did not result in a cooler average temperature.

Snow accumulation has remained on arrays for as long as a week (of sunny weather). On the integral and direct mount arrays the snow tends to slide off all at once when sunny weather returns after a storm. Snow on the stand-off arrays tends to melt in place, greatly prolonging the time the array takes to clear.

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*This work was sponsored by the U.S. Department of Energy.
**The U.S. Government assumes no responsibility for the work presented.
+Presented at the Fourth Photovoltaic Systems Integration Meeting, 12-14 April 1983, Albuquerque, New Mexico.
ENERGY PRODUCTION SUMMARY
NE RES PROTOTYPE SYSTEMS

ENERGY PRODUCTION COMPARISON NERES-SHRES
TRISOLARCORP PROTOTYPE SYSTEM

POWER CONDITIONER ENERGY EFFICIENCY
NE RES PROTOTYPE SYSTEMS

PREDICTED (TMY) AND MEASURED GENERATION
NERES TRISOLAR PROTOTYPE
**Operating Power Conditioner Units at Northeast Res**

<table>
<thead>
<tr>
<th>Year</th>
<th>MIT</th>
<th>WEST</th>
<th>G.E.</th>
<th>TribSolar</th>
<th>Solarex</th>
<th>Carlisle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1981</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>1982</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

**Snow Shedding at the NERES**

February 1982

**Measured Effect of Sampling Rate on Utility Interaction Calculations**

**Snow Data: February 9–10, 1983**

Actual vs. Predicted System Energy Production
At the Northeast Residential Experiment Station in Concord, Massachusetts, residential photovoltaic systems have been under evaluation for over two years. In this time numerous experiments have been conducted and copious amounts of data have been recorded and analyzed. The site has experienced a wide range of meteorological conditions associated with a four-season climate region, to stress the systems. Numerous reports have been published on results and findings over this two-year period, and reporting continues unabated. Given the experiences of designing, constructing, evaluating and troubleshooting these prototype, first of their kind residential PV systems, many of the predictions relating to system design or performance have been studied and verified or disproved. We now have a much clearer picture of the significant design considerations, and a much better understanding of how a residential PV system should be designed to achieve the best possible performance, for the least possible cost.

The features of the "best" achievable system which can be built today will be presented. In all cases the recommendations are based upon the NE RES system experiences, and rationale is provided where necessary. Four categories have been derived for which the recommended system characteristics are delineated: PV module, PV array mount, PV array wiring, and the power conditioner. Where applicable, the status of the NE RES prototype systems is reviewed in terms of meeting the criteria for the "best" system.

Additional technical issues regarding PV system performance or design which are presently being addressed, or scheduled for this calendar year are also described. At the NE RES, the focus of activity for 1983 will be on evaluation of retrofit PV system designs. Unlike the first generation prototype systems, that is, those currently in place, retrofit systems are expected to be small (in the 2-4 kWp size range), will have to be mounted on roof slopes in the range 18-30 degrees, and there will likely be no available access to the attic space beneath existing roofs of such tilts. Such constraints will present a new set of concerns for both system design and installation as well as troubleshooting/maintenance. Retrofit system experiments will focus on achieving low-cost array roof-mounting schemes, and on improving the heat transfer characteristics of stand-off mount PV arrays. The latest in available PV module hardware will be used, and National Electrical Code-approved system designs will be built. Heretofore the power conditioners in the 2 kW size range have been all but ignored by the present set of operating systems which are not suited for use with the smaller units. Continued experiments on understanding the factors affecting snow shedding will also be conducted. It is expected that at the lower array tilt angles and with the stand-off mount arrays, snow shedding will become a problem of increasing proportion; system designs will address this concern.

In summary, the work over the past two years at the NE RES has led to a set of specifications, which are achievable with presently available hardware, for the best performing, least costly PV system. Areas which remain to be investigated regarding the system issues for a retrofit application are identified for work in the present calendar year.

*This work was sponsored by the U.S. Department of Energy.
**The U.S. Government assumes no responsibility for the work presented.
+Presented at the Fourth Photovoltaic Systems Integration Meeting, 12-14 April 1983, Albuquerque, New Mexico.
PV SYSTEM DESIGN SUMMARY

MILES C. RUSSELL
MIT ENERGY LABORATORY

14 APRIL, 1983

PV MODULE

- HIGH EFFICIENCY (≥ 10%)
  - reduce array size/installation cost
  - improve aesthetics

- LARGE MODULE (1 - 2 PERSON SIZE)
  - reduce installation cost
  - improve physical access
  - may improve cooling
  - may improve snow-shedding

- INTEGRAL BY-PASS DIODES
  - reduce field labor
  - reduce possibility of anti-parallel diode
  - can protect smaller groups of cells

- FRAMELESS DESIGN (AVAILABLE AS AN OPTION)
  - to accomodate simple integral mounting

- OPERATING VOLTAGE (15 - 25 V)
  - reduce minimum number to interface w/pcs
  - maximize flexibility to interface w/pcs

NE RES PV MODULE DATA

<table>
<thead>
<tr>
<th>ARRAY ENERGY EFFICIENCY (%)</th>
<th>MIT</th>
<th>WEST</th>
<th>GE</th>
<th>TSC</th>
<th>SX</th>
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<tr>
<td>JUL-DEC 82</td>
<td>7.3</td>
<td>7.1</td>
<td>4.8</td>
<td>9.3</td>
<td>5.5</td>
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</table>

<table>
<thead>
<tr>
<th>MODULE SIZE</th>
<th>LG</th>
<th>MD</th>
<th>SM</th>
<th>LG</th>
<th>LG</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>BY-PASS DIODES</th>
<th>FAC</th>
<th>FLD</th>
<th>NA</th>
<th>FLD</th>
<th>FAC</th>
</tr>
</thead>
</table>

| FRAMELESS       | YES | YES | NA | YES | YES |
| OPTIONAL ?      |     |     |    |     |     |

| OPERATING VOLTAGE 15-25 V | YES | YES | YES | YES | YES |
**BLOCK V PV MODULE DATA**

<table>
<thead>
<tr>
<th></th>
<th>ARCO</th>
<th>GE</th>
<th>MOBIL</th>
<th>SOLX</th>
<th>SPIRE</th>
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</thead>
<tbody>
<tr>
<td>MODULE EFFIC (%)</td>
<td>9.7</td>
<td>11.5</td>
<td>8.7</td>
<td>8.2</td>
<td>11.6</td>
</tr>
<tr>
<td>(1kW/m², 28C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODULE SIZE</td>
<td>MD</td>
<td>MD</td>
<td>LG</td>
<td>LG</td>
<td>MD</td>
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<tr>
<td>BY-PASS DIODES</td>
<td>FLD</td>
<td>FAC</td>
<td>FAC</td>
<td>FAC</td>
<td>FAC</td>
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<tr>
<td>FRAMELESS ?</td>
<td>NO</td>
<td>NA</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
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<tr>
<td>OPERATING VOLTAGE 15-25 V</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
</tbody>
</table>

**PV ARRAY WIRING**

- SERIES CONNECTIONS FIRST
  - allows for easy system expansion
  - simplifies installation
  - reduces wiring materials/cost
  - increased accessibility, simplifies diagnostics
- NEC - APPROVED CONNECTORS
  - polarized
  - no exposed live parts
  - latching or locking
  - ground: first make/last break
  - rated for interrupting string current
- NEC APPROVED CONNECTORS
  - polarized
  - no exposed live parts
  - latching or locking
  - ground: first make/last break
  - rated for interrupting string current

**PV ARRAY MOUNTING**

- NEW CONSTRUCTION: SIMPLE INTEGRAL MOUNT (WITH ACCESSIBLE ATTIC SPACE)
  - low materials cost
  - simple installation
  - dry wiring
  - ready electrical accessibility
  - ready mechanical accessibility
  - simple, effective cooling (venting)
  - no framing ridges, accelerates snow shedding

**POWER CONDITIONER**

- HIGH ENERGY EFFICIENCY (88 - 90 %)
- LOW DC TURN-ON THRESHOLD (≤ 50 W)
- QUIET (AUDIBLE NOISE ≤ 65dB @ 1 meter)
- MINIMIZED RADIO FREQ NOISE (not noticeable 1 room away)
- LOW NIGHTIME POWER DRAW (≤ 10 W)
- HIGH RELIABILITY
- WALL MOUNTABLE (≤ 100 LBS ?)
- HIGH POWER QUALITY (thd≤ 5%, pf≥ 1.0)
# NE RES Power Conditioners Data

<table>
<thead>
<tr>
<th></th>
<th>ABAC</th>
<th>ACHEV</th>
<th>APC</th>
<th>HELIO</th>
<th>WINDWIX</th>
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<tr>
<td><strong>Energy Efficiency</strong> (Jul-Dec 1982)</td>
<td>77.3</td>
<td>84.2</td>
<td>88.5</td>
<td>86.1</td>
<td>91.4</td>
</tr>
<tr>
<td>DC Turn-on Threshold (W)</td>
<td>750</td>
<td>65</td>
<td>40</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>Night Power Consumption (W)</td>
<td>6</td>
<td>48</td>
<td>3</td>
<td>17</td>
<td>7</td>
</tr>
<tr>
<td>Audible Noise</td>
<td>HI</td>
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<tr>
<td>Radio Noise</td>
<td>HI</td>
<td>MD</td>
<td>MD</td>
<td>MD</td>
<td>HI</td>
</tr>
<tr>
<td><strong>Reliability</strong> (Jul-Dec 1982 (%))</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Wall Mountable ?</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
</tr>
<tr>
<td>Power Factor (Full Power)</td>
<td>.96</td>
<td>.69</td>
<td>1.0</td>
<td>.99</td>
<td>.80</td>
</tr>
<tr>
<td>Current THD (%)</td>
<td>5.0</td>
<td>65.</td>
<td>1.5</td>
<td>4.4</td>
<td>15.</td>
</tr>
</tbody>
</table>

## PV System Issues 1983

**Retrofit PV Systems - Areas of Investigation**

- Low Cost Stand-off Mounts
- Code Approved Wiring Methods
- Thermal Properties/Characteristics
  - Sensitivity to roof pitch
  - Sensitivity to stand-off height
  - Sensitivity to mount/module geometry
- Snow Shedding at Shallow Roof Pitches (18° - 30°)
- Performance of 2kW Power Conditioners
- Performance of Block V/1983 PV Modules
The Southwest Residential Experiment Station (SW RES) has been in existence since September 1980. The first of eight FY81 prototype residential photovoltaic (PV) systems was activated in March 1981; the last in September of that year. Since that March 1981 event, the eight prototypes have produced more than 90 megawatt hours of rooftop-generated energy; some reliably, some not.

The goal of the SW RES is, broadly, to foster the early implementation of grid-connected residential PV systems. More specifically, our charter is to identify and resolve those technical and institutional issues that will influence widespread adoption of such systems. To fulfill this charter, the SW RES staff are involved in a variety of efforts beyond the prototype evaluation effort. Current activities include the fine-grained monitoring of five Las Cruces residences (non-PV); similar monitoring of two Las Cruces utility feeders (one of which serves the SW RES site and undergoes near-daily reverse power flow); and monitoring, via stand-alone data acquisition systems, grid-connected PV residences in Santa Fe, New Mexico, and Yuma, Arizona. We are involved, through work of the staff and feedback from the SW RES Consulting Committee, in institutional issues such as financing, insurance, codes, and utility-interconnection questions. Through publications, on-site visits, workshops, technical papers, and periodic data reports, we are sharing data, results, and conclusions with the public, the PV community, and the National Photovoltaic Program management.

Key results can be briefly stated: we see no significant technical barriers to grid-connected residential PV systems. Similarly, save the apparently-unsettled PURPA (Public Utility Regulatory Policies Act) issue, we foresee no major institutional barriers. Economic issues are still of paramount importance. It appears that value (to the homeowner) of roof-mounted energy will vary from state to state as a consequence of the states's PURPA implementations; this will probably strongly affect rate of implementation from one state to another.

There are many areas where technical questions remain. Some modules have failed, and the root causes are not yet known in all cases. Our second-generation inverters have been flawless and for the past six months all first-generation units have also been reliable, but high efficiency units at lower cost must be developed. We have many questions regarding array thermal behavior and are working to develop a better understanding of thermal phenomena. We have observed a fairly uniform shortfall between predicted and actual energy production performance of all FY81 prototypes and are evaluating data to identify reasons for this phenomenon.
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

CURRENT ACTIVITIES

Monitoring Prototype Performance
Monitoring Five Non-PV Residences
Monitoring Two PV Residences
Studying PV/Utility Interface
Issuing Data and Information
Planning "Flexible" Prototype
Ninth Prototype in Works

April 14, 1983
## SOUTHWEST RESIDENTIAL EXPERIMENT STATION—RESULTS AND ISSUES

### CHARACTERISTICS, FY81 PROTOTYPES

<table>
<thead>
<tr>
<th>Prototype System</th>
<th>Module Supplier</th>
<th>Array Area (m²)</th>
<th>Array Peak Power (kWP)</th>
<th>Mounting Method</th>
<th>Array Tilt (°)</th>
<th>Inverter Size</th>
<th>Inverter Supplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCO Solar</td>
<td>ARCO Solar</td>
<td>88.2</td>
<td>7.4</td>
<td>Direct</td>
<td>25</td>
<td>8 kW</td>
<td>Windworks</td>
</tr>
<tr>
<td>ARTU</td>
<td>ARCO Solar</td>
<td>55.2</td>
<td>4.9</td>
<td>Standoff</td>
<td>45</td>
<td>8 kW</td>
<td>Windworks</td>
</tr>
<tr>
<td>BDM</td>
<td>Motorola</td>
<td>54.0</td>
<td>4.5</td>
<td>Standoff</td>
<td>35</td>
<td>6 kW</td>
<td>Helionetics*</td>
</tr>
<tr>
<td>General Electric</td>
<td>General Electric</td>
<td>76.2</td>
<td>6.7</td>
<td>Direct</td>
<td>26.6</td>
<td>6 kVA</td>
<td>Abacus</td>
</tr>
<tr>
<td>Solarex</td>
<td>Solarex</td>
<td>68.4</td>
<td>5.1</td>
<td>Standoff</td>
<td>26</td>
<td>6 kVA</td>
<td>Abacus</td>
</tr>
<tr>
<td>TEA</td>
<td>Motorola</td>
<td>49.4</td>
<td>4.3</td>
<td>Rack</td>
<td>26</td>
<td>4 kW</td>
<td>APC*</td>
</tr>
<tr>
<td>TriSolarCorp</td>
<td>Applied Solar</td>
<td>58.0</td>
<td>5.3</td>
<td>Integral</td>
<td>30</td>
<td>8 kW</td>
<td>Windworks</td>
</tr>
<tr>
<td>Westinghouse</td>
<td>ARCO Solar</td>
<td>73.4</td>
<td>5.5</td>
<td>Integral</td>
<td>30</td>
<td>6 kVA</td>
<td>Abacus</td>
</tr>
</tbody>
</table>

*Replacement Inverter

April 14, 1983
## PROTOTYPE PERFORMANCE

<table>
<thead>
<tr>
<th>System</th>
<th>Days Down</th>
<th>Capacity Factor (%)</th>
<th>Actual/Predicted (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCO</td>
<td>0</td>
<td>16.2</td>
<td>92.5</td>
</tr>
<tr>
<td>ARTU</td>
<td>0</td>
<td>17.5</td>
<td>82.0</td>
</tr>
<tr>
<td>BDM</td>
<td>0</td>
<td>17.5</td>
<td>78.2</td>
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<tr>
<td>GE</td>
<td>27</td>
<td>13.4</td>
<td>69.2</td>
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<tr>
<td>SX</td>
<td>30</td>
<td>12.1</td>
<td>42.8</td>
</tr>
<tr>
<td>TEA</td>
<td>1</td>
<td>17.2</td>
<td>86.9</td>
</tr>
<tr>
<td>TSC</td>
<td>11</td>
<td>18.5</td>
<td>68.6</td>
</tr>
<tr>
<td>WST</td>
<td>7</td>
<td>15.8</td>
<td>61.0</td>
</tr>
</tbody>
</table>

April 14, 1983
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

FAILURES, PROBLEMS, AND CURES

Major Abacus Fix May 18-20, 1982
High Site Line Voltage (DECC, APC, ARTU)
ARTU Isolation Transformer
Loosening power connections - SX Abacus
ARCO Module & Wiring Shorts
Solarex Modules - 5 discovered October 8, 1982
GE Shingles - Problem surfaced November 11, 1982
Loosening power connections - TSC Gemini - October 12, 1982
TSC Gemini Failure July 13-15, 1982
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

ADDITIONAL PROTOTYPE USING RIBBON TECHNOLOGY

FP Mailed May 14, 1982
Three Proposals Received June 15
Selection June 16: Mobil Solar Energy
Contract Awarded August 1
Preproduction Modules September 22 - BAD NEWS
Delay Granted September 27
CDR Held March 21
Prototype Acceptance Late June 1983
HAWAII LIVED-IN RESIDENTIAL PV SYSTEMS -- RESULTS AND ISSUES

George D. Curtis
Technical Coordinator
Hawaii Natural Energy Institute
University of Hawaii at Manoa
Honolulu, Hawaii 96822

ABSTRACT

The 2 KWP and two 3.5 KWP, utility-backed PV systems installed in lived-in residences by ARCO in cooperation with HNEI and DOE are described briefly. Monitoring, reporting, and maintenance are performed by HNEI under contract from Sandia National Laboratories.

Several precepts developed and lessons learned during installation and initial operation are presented. Much of this has recently been published by the DOE (ref. A). Most problems have occurred with inverters; however, once a defective unit was replaced the failures were relatively minor and random. None of the 280 PV modules has failed.

Performance has been affected by a long period of high rainfall/low insolation (see figure). In spite of the clouds, the energy produced has far exceeded that available from a concentrator system. The generally cool weather has apparently contributed to system efficiency. A number of variables and factors (see figure) such as wind, cell temperature, etc., are to be analyzed to quantify such correlations. The data reduction program permits ready examination of individual parameters for this purpose.

Time mismatch between production and load occurs at the residences in spite of the occupant's efforts (see figure) and reduces the economic benefit. This will be improved at one site by connecting four units of a quadraplex to one PV system. The electrical distribution and metering are depicted in the figure.

The systems are now mature enough that applied experiments such as the redistribution scheme, trials of new inverters, examination of second order effects, etc., can be performed confidently in a real-world environment. The basic issue to be faced is, as often the case, economics.

REFERENCES

HNEI RESIDENTIAL PV

Work in Progress:

1. Retrofit 4KVA American Power Inverter at Pearl City site
2. Retrofit 2KVA DECC Inverter at Kalihi site
3. Monitor and evaluate results of above changes
4. Re-wire and re-meter entrance wiring to quadruplex to distribute PV energy more economically
5. Monitor and evaluate effects of above changes
6. Examine effects of removal of baffles, effects of wind, temperature, etc., on performance
7. Continue to monitor system performance and possible degeneration
HOME DEMAND AND PV PRODUCTION
MODIFICATION OF THE PEARL CITY PV SYSTEM TO SERVE ALL FOUR UNITS

Rooftop System

Power Conditioning Unit (PCU)

PV Meter*

Unit 'A' meter*

Unit 'B' meter*

Unit 'C' meter*

Unit 'D' meter*

* indicates monitored by HNEI data logger
R indicates revenue meter - HECO reads only these
Cumulative and monthly average energy production at each PV site, and cost factors at 1982 rates.

<table>
<thead>
<tr>
<th>Total energy generated/exported/imported to date (kWh), as of Feb. 28, 1983</th>
<th>KALHI</th>
<th>PEARL CITY</th>
<th>MOLOKAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERATED</td>
<td>EXPORTED</td>
<td>IMPORTED</td>
<td>GENERATED</td>
</tr>
<tr>
<td>2816</td>
<td>1400</td>
<td>5802</td>
<td>8515</td>
</tr>
</tbody>
</table>

Average energy generated/exported/imported (kWh) per month

<table>
<thead>
<tr>
<th>PER MONTH</th>
<th>KALHI</th>
<th>PEARL CITY</th>
<th>MOLOKAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>148</td>
<td>73</td>
<td>305</td>
<td>405</td>
</tr>
</tbody>
</table>

ENERGY SAVINGS
- Kalani energy savings to date: $239.92
- Pearl City energy savings to date: $595.50
- Molokai energy savings to date: $919.51

Calculations
- Normal utility bill = (1) + (3)
- New utility bill = (3) - (2)
- Energy savings = Normal bill - New bill
INSOLATION AND ENERGY PRODUCTION FOR THREE HAWAII PV RESIDENCES

KWH, generated

INSOLATION

KWH/m²

MOLOKAI [8389 kWh]
PEARL CITY [8515 kWh]
KALIHI [2816 kWh]

PEARL CITY

MOLOKAI

KALIHI


1981 1982 1983
Strip chart record of global insolation in Honolulu and hourly average insolation and standard deviation at nearby Pearl City site. Standard deviation indicates cloud passages.
ABSTRACT

D. F. Menicucci

AN ASSESSMENT OF MISSING RESIDENTIAL PV DATA AND A PLAN FOR FUTURE NEEDS WITHIN DOE'S "HIGH RISK" RESEARCH PROGRAM

The DOE sponsored residential programs have produced massive technical data bases. It is estimated that the computerized and hand-logged data files created by DOE's Residential Experiment Stations (RES) measures over one billion characters. These data, if packed at the density of a typical encyclopedia, would fill over 250 bound volumes on a 40 foot library shelf. Despite the enormous size of this data base concerns have been raised about various record gaps that may affect the overall data quality and especially data summaries. In this situation data for a parameter are present but, because of some missing values, it's feared that the records don't accurately represent reality. Other concerns relate to gaps that exist because certain parameters are not being measured. In this event a class of data is missing and leaves the user with no chance to quantify reality. Each of the two types of missing data is important. However, the second type of gap is clearly more serious. Missing values in a record can often be either estimated or ignored but when a class of data is missing an analyst may be unable to complete an analysis or make a vital decision. For example, a missing data class may inhibit a potential user from a decision to invest in PV.

A methodology was developed to identify the potential data class gaps. The methodology is logically based and employs a top-down process which begins with the consideration of the objective of the DOE PV program and results in a detailed outline of information and data that are needed to meet the program goals.

The application of the methodology is described in detail. The DOE PV program objective is outlined and analyzed and the implications of the "high risk" research are considered from the view of a potential end product user. In central focus are the informational requirements that are possibly not being fulfilled by the DOE program and may inhibit the utilization of residential PV in the private sector. A specific set of analysis tasks are suggested to meet these informational requirements. The development of each task begins with the use of the existing residential data base. Where data classes are perceived to be missing specific experiments are proposed. The final result of the effort is an experimental plan through which the necessary information and data will be available for the private sector to develop and utilize residential PV systems in the US.
UTILITY INTERESTS IN RESIDENTIAL PV

George J. Vachtsevanos
Georgia Institute of Technology
Engineering Experiment Station/Technology Applications Laboratory
Atlanta, Georgia 30332

As part of the Southeast Residential Experiment Station (SERES) program funded by the Department of Energy, work was initiated in January 1983 to address utility concerns arising from the introduction of residential PV systems into the power distribution network. A cohesive and unique five year program of research has been defined by the SERES Utilities Research Group in cooperation with Georgia Tech bringing together electric utility companies and a university research team into a comprehensive effort focused at photovoltaic-utility interactions.

The major areas of research include such issues as: fault protection and safety; current and voltage harmonics generation and propagation; voltage regulation and reactive power compensation; "islanding" or isolated operation; utility operations research involving both distribution and overall grid system analysis. Although it is generally agreed that all of these issues will impact significantly the utility-PV system interface, the focus during the first two years of the project is upon problems associated with fault protection and harmonic current and voltage propagation along the power lines.

A combination of experimental and analytical approaches has been adopted to arrive at solutions to the protection and harmonic problems. Experiments will simulate fault conditions and power conditioning induced harmonics on utility feeders with grid-connected photovoltaic systems. The experimental results will be evaluated and data used for model verification purposes and more extensive computer simulation studies. Simulation results, on the other hand, will guide the experimental design.

Protection of the utility distribution system connected to photovoltaic sources includes proper protection under faulted conditions so that the reliability of service remains unaffected and equipment damage is avoided. Transient and resonant overvoltages, power conditioner faults and line faults may adversely affect system operations. Specific problem areas include fault current contribution, recloser coordination, fault sensitivity and detection ability and the effect of increased short-circuit capacity with PV sources present. The second major phase of the program will study the propagation of current and voltage harmonics on utility lines and assess the impact of various levels of PV penetration on harmonic-induced resonance problems and metering and billing practices.

As this program is entering the testing and analysis phase, Georgia Tech is responsible for working with the utility companies in the conduct of the test program and for reflecting these tests into analyses of issues of concern to the utility companies as they confront the integration of PVs into their distribution networks. On the experimental side, a frequency selective impedance bridge has been designed to measure distribution line impedance levels with an acceptable accuracy. Test procedures are being designed to measure harmonic content. Candidate sites are being evaluated for the fault studies and suitable instrumentation is considered. A PV system model is in the final stages of development and a transient analysis program is being modified to include the dynamic characteristics of typical distribution networks encountered in the Southeast.
UTILITY INTERESTS
IN RESIDENTIAL PV

FOURTH PHOTOVOLTAIC SYSTEMS INTEGRATION MEETING

GEORGE J. VACHTSEVANOS
GEORGIA INSTITUTE OF TECHNOLOGY
APRIL 1983
ISSUES:

A. TECHNICAL
B. ECONOMIC
C. INSTITUTIONAL

TECHNICAL ISSUES

1. PROTECTION AND SAFETY
2. VOLTAGE AND CURRENT HARMONICS
3. VOLTAGE REGULATION AND REACTIVE POWER COMPENSATION
4. "ISLANDING" OR ISOLATED OPERATION
5. UTILITY OPERATION:
   - DISTRIBUTION SYSTEM ANALYSIS
   - GRID SYSTEM ANALYSIS
TECHNICAL ISSUES ADDRESSSED BY SERES
FIRST 2-YR PERIOD

1. FAULT PROTECTION
2. HARMONIC PROPAGATION

APPROACH TO TECHNICAL ISSUES

OPTIMUM RESULTS OBTAINED BY AN
INTERACTIVE "DUAL" ANALYTICAL/EXPERIMENTAL APPROACH

1. EXPERIMENTAL TESTING –
   CONDUCTED BY PARTICIPATING SOUTHEAST UTILITIES
   UNDER THE GUIDANCE AND LEADERSHIP OF GIT

2. COMPUTER SIMULATION STUDIES –
   CONDUCTED BY GIT
EXPERIMENTAL PROCEDURE

A. DISTRIBUTION FAULT PROTECTION
- Present protection philosophy
- Problems with the addition of dispersed PV generators
- System protection from line faults
- Conceptual design and performance of appropriate protection strategies

B. HARMONICS EXPERIMENTS
- Distribution line impedance characterization
- Background harmonic content
- Voltage and current harmonics measurements
- Resonance phenomena
- Impact upon utility operations and practices
- Control strategies
PV SYSTEM MODEL

A MODULAR APPROACH TO SIMULATING
THE DYNAMIC BEHAVIOR OF

- THE PV ARRAY
- DC INTERFACE
- INVERTER
- AC INTERFACE

DISTRIBUTION NETWORK MODEL

A MODULAR AND INTERACTIVE APPROACH
TO SIMULATING THE TRANSIENT AND
FREQUENCY DEPENDENT CHARACTERISTICS
OF THE DISTRIBUTION NETWORK
PV SYSTEM MODEL

PV ARRAY → DC INTERFACE → INVERTER → AC INTERFACE → ELECTRIC GRID
TYPICAL DISTRIBUTION FOR SYSTEM SIMULATION PURPOSES

- Distribution Substation
- 12kV Overhead Line
- 3-Phase Cable
- Single Phase Cable
- Single Phase Cable
- Step Down XFMR
- Isolation XFMR
- PV System
- Isolation XFMR
- PV System
RESIDENTIAL PHOTOVOLTAIC INSTALLATION COSTING

David A. Penasa
Uhl & Lopez Engineers, Inc.
Electrical Consulting Engineers
213 Truman, N.E./P.O. Box 8790
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(505) 265-3425

Abstract

For this report, prepared under a contract with Sandia National Laboratories, detailed installation costs were estimated for the following four reference residential photovoltaic systems designed by the General Electric Company, Energy Systems and Technology Division:

1. The Design of a Photovoltaic System with On-Site Storage for a Southwest All-Electric Residence
2. The Design of a Photovoltaic System for a Passive Design Northeast All-Electric Residence
3. The Design of a Photovoltaic System for a Temperate Climate All-Electric Residence.
4. The Design of a Photovoltaic System for a Southeast All-Electric Residence.

Installation costs were evaluated for each design using (1) union (Davis-Bacon) wage scales and (2) non-union (non Davis-Bacon) wage scales.

The costs were then presented in a format familiar to the P-V community.

The final report, entitled "System Cost Analysis for Reference Residential Photovoltaic Designs" was delivered to Sandia National Laboratories for publication in July of 1982.
Description of Reference Residential Photovoltaic Designs

1. The Design of a Photovoltaic System with On-Site Storage for a Southwest All-Electric Residence (e.g. Albuquerque, NM):

- 6.07 KW stand-off, grid connected array using 100 Solarex Block IV modules.
- Modules mounted on wood 2" x 4" stand-offs with conventional asphalt shingles beneath the modules.
- P-V module frame fits into aluminum clips mounted to stand-offs and attaches to the clips by sheet metal screws. Electrical interconnections between modules are made by cables with plug-in connectors.
- 25 KWH lead acid battery storage subsystem.
- 6 KVA line-commutated inverter/10 KVA isolation transformer.
- System operation is parallel and synchronized with the utility, without feedback. Excess generated power is shunted to ground.

2. The Design of a Photovoltaic System for a Passive Design Northeast All-Electric Residence (e.g. Boston, MA):

- 4.1 KW direct mounted array using 56 General Electric shingle modules.
- Modules are directly mounted on top of the roofing felt and plywood sheathing.
- Modules are installed by an overlapping procedure similar to conventional shingles. Each shingle module is electrically interconnected by two flat conductor cables. Standard roofing nails are used for attachment to the roof.
- 4 KVA line-commutated inverter/5 KVA isolation transformer.
- System operation is parallel and synchronized with the utility. Excess generated power is fed back to the utility.
Description of Reference Residential Photovoltaic Designs

3. The Design of a Photovoltaic System for a Temperate Climate All-Electric Residence (e.g. Santa Barbara, CA):

- 4.29 KW array using 50 Solarex modules similar to Block IV residential module but with sealant strips attached for mounting.

- Modules and mounting accessories which may be used either as an integral mount or as a standoff mount.

- Modules are mounted on a series of channel supports which can be placed on the roof truss for an integral mount or on a shingled roof for a standoff mount. An overlapping seam is used between modules to shed water. Electrical connections are made with cables equipped with plug-in connectors.

- 4 KVA inverter.

- System is parallel and synchronized with the utility. Excess generated power is fed back to the utility.

4. The Design of a Photovoltaic System for a Southeast All-Electric Residence (e.g. Miami, FL):

- 5.6 KW array using 98 Solarex Block IV modules into an integral mount design.

- Modules and mounting extrusions are secured on the roof rafters and the horizontal roof purlins.

- Mounting extrusions are attached to the rafters with screws. The modules are then bolted to the mounting extrusions. This compresses an elastomeric material to form a seal.

- Electrical connections are made with cables equipped with plug-in connectors.

- 6 KVA inverter

- System is parallel and synchronized with the utility. Excess generated power is fed back to the utility.
Description of Installation Costs in Format Familiar to P-V Community

Each estimate was broken down into the following items:

a. Installation of P-V Array ($/Watt peak)
   
   This item includes materials and labor required to install the P-V modules, taking into account any roof credits for items which would be installed as part of a normal roof, but does not include the cost of the modules or wiring interconnections.

b. Installation of Power Conditioning System ($/job)
   
   This item includes labor required to install the PCS unit, but does not include the cost of the PCS unit.

c. Installation of Battery Storage System ($/kwhr)
   
   This item includes materials and labor required to install the battery storage system, including interconnections, enclosures, racks, etc., but does not include the cost of the batteries.

d. Power Wiring ($/job)
   
   This item includes materials and labor required to wire the P-V system, including P-V module interconnections, disconnect switches, blocking diodes, junction boxes, conduit and wire, connections between the P-V array and the PCS, connections from the PCS and the house electrical panel, etc.; but does not include electrical items, such as the electrical service drop, electrical panel or other items installed in a normal residence.

e. Subcontractor Markup ($/job)
   
   This item includes markups the subcontractor adds to his price to cover overhead, profit, bid bond and gross receipts tax.

f. Fringes and Benefits ($/job)
   
   This item includes markups the subcontractor adds to his price to cover extra labor costs for fringes, benefits and any other items not included in his bare labor cost.

g. Prime Contractor Markup ($/job)
   
   This item includes the markup the prime contractor adds to the subcontractor's price to cover handling of the subcontractor's work.

h. Total ($/Watt peak) + ($/kwhr)
   
   This item describes the total residential P-V system installation cost in terms of array size and battery size (if applicable) excluding the costs for the P-V modules, PCS unit and batteries.
Example:

COSTS FOR INSTALLATION OF P-V SYSTEM WITH ON-SITE STORAGE
FOR A SOUTHWEST ALL-ELECTRIC RESIDENCE*

LOCATION: Albuquerque, New Mexico
P-V MODULE TYPE & MOUNTING: Solarex, Stand-off
WAGE SCALES USED: Davis-Bacon (Union)

COSTS:

1. Installation of 6.07 kWp P-V Array
   $/Watt peak
   .13 (material)
   .34 (labor)

2. Installation of Power Conditioning System
   $/job
   -0- (material)
   411 (labor)

3. Installation of 25 kwhr Battery Storage System
   $/kwhr
   79 (material)
   38 (labor)

4. Power Wiring
   $/job
   953 (material)
   1816 (labor)

5. Subcontractor Markup
   $/job
   750 (material)
   1380 (labor)

6. Fringes and Benefits
   $/job
   790 (labor)

7. Prime Contractor Markup
   $/job
   186 (material)
   253 (labor)

8. Total
   $/Watt peak +
   $/kwhr
   .36 (material) +
   99 (material)
   1.08 (labor) +
   58 (labor)

*Assumes a June 1982 midpoint of construction.
The table below indicates a summary of the total installation costs for the reference residential photovoltaic designs, assuming a June 1982 midpoint of construction.

Cost Summary - Photovoltaic Power Systems Total Installation
Costs for Reference Residential Designs

(All costs are in dollars per peak watt, battery storage system costs are in dollars per kilowatt-hour. Purchase costs for P-V modules, power conditioner, batteries and battery charging system are not included.)

<table>
<thead>
<tr>
<th>Location</th>
<th>System Description</th>
<th>Union Labor</th>
<th>Non-Union Labor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southwest</td>
<td>P-V system</td>
<td>.36 (material)</td>
<td>.36 (material)</td>
</tr>
<tr>
<td>All-Electric (with Battery Storage)</td>
<td></td>
<td>+1.08 (labor)</td>
<td>+.86 (labor)</td>
</tr>
<tr>
<td>Albuquerque, NM</td>
<td></td>
<td>1.44 (total)</td>
<td>1.22 (total)</td>
</tr>
<tr>
<td>Northeast</td>
<td>Battery Storage</td>
<td>.99 (material)</td>
<td>.99 (material)</td>
</tr>
<tr>
<td>All-Electric (Direct Mount Shingle P-V Array)</td>
<td></td>
<td>+ .58 (labor)</td>
<td>+.43 (labor)</td>
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<td>Boston, MA</td>
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<td>1.57 (total)</td>
<td>1.42 (total)</td>
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<td>Temperate Climate</td>
<td>P-V System</td>
<td>.54 (material)</td>
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<tr>
<td>All-Electric (Integral Mount P-V Array)</td>
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<td>+1.09 (labor)</td>
<td>+.86 (labor)</td>
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<tr>
<td>Santa Barbara, CA</td>
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<td>1.63 (total)</td>
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<td>Southeast</td>
<td>P-V System</td>
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<tr>
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<td>+1.33 (labor)</td>
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<td>2.12 (total)</td>
<td>1.83 (total)</td>
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<td>Southeast</td>
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<td>All-Electric (Integral Mount P-V Array)</td>
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<td>+ .82 (labor)</td>
<td>+.65 (labor)</td>
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<tr>
<td>Miami, FL</td>
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<td>1.46 (total)</td>
<td>1.29 (total)</td>
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</table>
COST GOALS VERSUS ACTUAL ESTIMATED COSTS

A. Department of Energy (DOE) Cost Goals:

Goals were established in 1980 by the DOE under the National Photovoltaics Program for photovoltaic modules, power conditioners and systems used in residential, intermediate and central station applications in terms of purchase and installation costs for the next decade (through the year 1990).

Photovoltaic Power System Costs - Residential

<table>
<thead>
<tr>
<th></th>
<th>1986 DOE Goal</th>
<th>1980 Status (per DOE)</th>
<th>1986 DOE Projected New</th>
<th>1986 DOE Projected Retrofit</th>
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<td>Array</td>
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<tr>
<td>Purchase</td>
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<td>Purchase</td>
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<td>0.04</td>
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<td>0.08</td>
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<td>Operate</td>
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<tr>
<td>Maintain</td>
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<td></td>
<td>0.10-1.43</td>
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<td>21.30-22.84</td>
<td>1.78-2.78</td>
<td>2.39-3.48</td>
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</table>

(All costs in 1980 constant dollars per peak watt)

B. Actual Estimated System Costs for Reference Designs:

Photovoltaic Installation Costs by System - Reference Residential Designs

Array and Power Wiring

<table>
<thead>
<tr>
<th>June 1982</th>
</tr>
</thead>
</table>

| Installation |  |
|--------------|------------------|------------------|------------------|------------------|
| Stand-off    | 0.79-1.48        | Integral         | 0.96-1.11        | Direct           | 1.10-1.17       |
| Power Conditioner | 0.05-.11 | ** (excluding markups) | |

<table>
<thead>
<tr>
<th>TOTAL INSTALLATION</th>
<th>1.22-2.12</th>
</tr>
</thead>
</table>

(All costs in dollars per peak watt)

* Excludes purchase cost of p-v modules

** Excludes purchase cost of power conditioner

*** Excludes purchase cost of p-v modules and power conditioner
CONSIDERATIONS RELATED TO INSTALLATION - SUGGESTIONS, COMMENTS, POTENTIAL PROBLEMS

A. Additional Costs:

The cost estimates prepared in this report were intended to detail complete installation costs, excluding equipment costs for p-v modules, power conditioner and batteries.

While these estimates take into account a credit for roofing materials normally required for a residence, but not required because of the photovoltaic system, they do not take into account other less obvious additional costs or savings such as the additional design fees, solar tax credits, additional insurance coverage and increased property taxes.

B. P-V Array Mounting Methods:

The reference residential p-v designs analyzed in this report utilize three types of module mounting: stand-off, integral and direct. The estimates prepared indicate the stand-off method and the integral method are the most expensive, depending on the design, while the direct method appears to be the least expensive for the given designs.

The mounting method to be used for a given residence should be carefully chosen based upon selection of p-v modules, availability of custom support materials, aesthetics, whether the installation is new or retrofit and available roof area. These items can affect both cost and desirability of the mounting method.

C. Design Comments:

1. Custom Materials:

The mounting methods detailed in the reference residential designs are somewhat theoretical in that they utilize materials, such as aluminum extrusions and elastomeric materials, which were optimized from a design standpoint, but which were not necessarily based upon presently available stock items.

These materials will have to be made on a custom fabrication basis until standard configurations are developed for mounting. This will come with the standardization of manufacturer's p-v module sizes and module framing members.

2. Responsibility for Installation:

Responsibility for the p-v module installation needs to be carefully considered in residential designs. Because of the newness of p-v installations, no precedent has been established as to which tradesmen are to perform the module installation. Since several trades would be involved in the installation, it should be clearly specified as to who is responsible for performing each of the required installation tasks. This way, jurisdiction would be established and responsibility for warranty clearly defined.
CONCLUSION

P-V Systems hold great promise as a source of electrical power for residential use. If costs for major equipment components (p-v modules, inverters and batteries) continue to decline, p-v systems could provide residential energy at prices competitive with utility rates by 1986.

At present, major equipment component costs appears to be the primary area of concern for reducing total p-v system costs. (Presently, purchase costs for p-v modules and the inverter used in a typical residential application total approximately $10 to $12 per watt peak while installation costs, as determined in this report, range from $1.22 to $2.12 per watt peak).

But, if DOE cost goals are met, by 1986 the installation costs will be roughly equal to the major equipment component costs.

Therefore, more work should be initiated to develop new innovative installation methods, particularly for the p-v arrays, which are simpler and based upon the use of cheaper materials.
CONTRACT STATUS SUMMARIES
Reliability and performance of a utility intertie inverter have been improved and production costs have been reduced significantly. Abacus Controls Inc. built its first utility intertie "Sunverter" in 1977 and delivered it in 1978. Since then, twenty-one sunverters have been built and operated by various government, industrial, and foreign customers. Accomplishments under the present contract take full advantage of earlier field experience and information feedback to produce a "next generation" sunverter suited for production quantities of 2,000 per annum.

Previously built sunverters were custom wired from schematic diagrams on a point-to-point basis. The primary technique for cost reduction in the new design is a back plane master printed circuit card, which contains over 3/4 of the wires that were previously inserted by hand. Also contributing to reduction in cost are the elimination of two relays that are replaced by inexpensive integrated circuits, lower cost power transistors, and a six-deck three-position switch reduced to a two-deck switch mounted directly on the master printed circuit card. Troubleshooting has been improved with the addition of a mimic bus and fault identifying LED lamps on the master printed circuit card. The number of control transformer secondary windings have been reduced from seventeen to five.

The size of the sunverter is 33"h x 25.6"w x 15.2"d. The upper section, which contains the electronics and the master printed circuit card, is dust tight and drip proof. Heat is removed through thermalloy extrusions, which are mounted on the sides of the sunverter near the top. The bottom section, which contains transformers and large capacitors, is cooled via ventilation holes with the inlets on the bottom and the outlets on the sides. The sunverter is maintained 4" off the floor to allow for the presence of a small amount of standing water.

A reliability improvement has been achieved with the isolation of all low voltage logic and control circuitry from both the array and the utility line. A Royer oscillator power supply isolates the DC interface while optical isolators are used to couple signals to the power transistors.

Three sunverters of the improved design, Model 743C-4-200, have been built for Sandia National Laboratories, and two others have been built for other customers. Assembly labor in small quantity is running 30% of what the earlier models required. Test time is also significantly reduced.
A secondary task is the design, development, and manufacture of a prototype battery management circuit to interface between an array, a battery, and the inverter. Nominal array voltage is 200V, with normal excursions of the max power point between 160V and 240V. Nominal battery voltage is 132V. The battery charger contains a step-down charging circuit when the array charges the battery and a step-up DC-DC converter when the battery supplies power to the sunverter. The sunverter is capable of operating in the stand-alone (uninterruptible power supply) mode as well as the utility intertie mode; the presence of the battery in the system enhances power availability.
INTERMEDIATE PHOTOVOLTAIC SYSTEM APPLICATION EXPERIMENT
G. N. Wilcox Memorial Hospital, Kauai, Hawaii

D. Rafinejad
Acurex Solar Corporation
Mountain View, California 94042

Wilcox Hospital photovoltaic (PV) project was designed, constructed, and operated by Acurex Corporation. The system is rated at 35 kW of direct current electrical power and 200 kW (0.68 million Btu/hr) of thermal energy at the design condition of 1,000 W/m² of direct normal insolation and 50°C cell temperature.

Funding was provided in part (77 percent) by the U.S. Department of Energy (DOE) under its Concentrating Photovoltaics Application Experiment Program, with the State of Hawaii providing funding (23 percent) administered through the Hawaii Natural Energy Institute (HNEI). The technical monitor for the program was Sandia National Laboratories in Albuquerque, New Mexico.

The overall objectives of this project were to: (1) demonstrate the technical feasibility of a concentrating PV solar energy system in the State of Hawaii; and, (2) provide practical operating experience of a PV total energy (electricity and heat) system in conjunction with a hospital.

The Wilcox Hospital in Lihue, Kauai was chosen as the site for the PV system because the hospital can use both the electrical and thermal energy provided by the PV system. The main energy loads for the hospital are air conditioning and hot-water heating. The air-conditioning requirement peaks near midday and in the summer, corresponding to solar energy availability. The Hawaiian location at 22°N latitude provides excellent insolation, although the Lihue climate proved to be less than ideal for a concentrating solar system. Also, because Hawaii is so dependent on expensive imported fuels, solar energy will become cost effective in Hawaii before continental sites.

The PV system is designed to supply electricity to the hospital grid, and heat for domestic hot water. The electricity is generated from PV cells along the focal line of the parabolic trough concentrators. The PV collector field is made up of 10 groups consisting of 8 collectors in each row. Each collector is 6 ft by 10 ft in aperture. The collectors are oriented with their axes aligned along the true north-south direction for minimum incidence and end losses. The groups are connected in series to form a single serpentine flow loop. The parabolic trough surface reflects and concentrates the sunlight onto two faces of the PV receivers. A total of 108 cells, manufactured by Applied Solar Energy Corporation, are mounted on a 10-ft-long "V"-shaped receiver tube with 54 cells on each face of the "V." Each receiver contains 3 strings of 36 cells in parallel. A bypass diode is in parallel with each group of three cells to maximize fault and shadowing tolerance. The resulting electrical power is converted and conditioned by the power conditioning system to supply alternating current electricity at 480V, 3 phase to the hospital, eliminating the necessity for electrical storage.

The thermal energy and cell cooling system consists of a closed-loop coolant circuit; a 3,000-gal storage tank with an immersion-type heat exchanger for heating the hospital potable water; and a coolant circulation pump and finned tube cooling convectors for rejecting excess heat. The coolant fluid is water that has been treated to boiler feedwater standards. As a result of the mild temperatures at the site, no antifreeze is required. All hospital hot water is preheated in the storage tank using any available heat and then brought up to the final temperature in the existing hot water heaters. The cooling convectors are used to reject any excess collected heat which is not used in the storage tank.

The power conditioning unit (PCU) has two distinct functions. The first is to hold the field at its peak power point, and the second is to produce alternating current power compatible with the utility. A sophisticated 12-pulse, self-commutated inverter manufactured by Westinghouse Corporation is used to convert the direct current field output to suitable alternating current.
energy. The peak power tracker and inverter are controlled by a microprocessor system incorporated into the unit. The output of the inverter can be fed directly into the main electrical distribution bus at the hospital in parallel with the utility service. In this way, all of the field output is used at all times by offsetting the utility usage. There is no electrical energy storage in the system.

Sandia National Laboratories has assembled a computer-based operational data acquisition system (ODAS) which monitors system performance at all times. The system measures weather parameters, system temperatures, and both alternating and direct current electrical performance. These values are gathered at 1-min intervals and averages are recorded at 10-min intervals on magnetic tape. The system data is linked to Boeing Computer Services by telephone for further evaluation. The ODAS was recently removed by Sandia after 1.5 years of operation.

Operation of the field is fully automatic. The collectors spend nighttime and stormy periods in a "face down" position. When the solar radiation is sufficient to allow operation of the unit at a net positive power flow, the collectors "wake up" and focus on the sun. The coolant flow is automatically started at the same time. When sufficient power is available to operate the PCU it will turn on automatically. Should anything go wrong during operation an annunciator panel will inform the operator of the source of the problem while the automatic controls cause an appropriate response. The ODAS can detect all problems and will keep a record of system problems along with the other data.

The system was built by Acurex between February and September of 1981. An extensive factory assembly was used to minimize cost. The construction cost was a factor of two lower than the lowest competitive bid obtained at the conclusion of the design. Collector operation was checked before the receivers were installed so that the controls could be fully evaluated without risking any damage to the receivers. The flow system was then flushed and checked. The collectors were brought to focus and the PCU was checked out.

Two major problem areas were encountered during system startup. The first was degradation of the cell modules on the photovoltaic receivers, which had not previously occurred during hundreds of hours of prototype testing. The PVB material which bonds the cells to their glass superstrate was bubbling. This overheating of the PVB was caused by a manufacturing quality control problem at Acurex, and was corrected by opening the receivers and adding sufficient thermal grease.

The second problem area was the apparent inability of the PCU to sustain operation in parallel with the utility grid. This problem was caused by voltage fluctuations in the Kauai electric grid. Westinghouse made modifications to the unit which restored reliable operation. These changes were completed in a fairly short period, and the system was able to come online and operate within specification.

The poor weather during 1982, the worst in 50 years, prevented the system from producing the expected level of energy. In addition, due to the extended weather-related downtime, moisture penetration in the receiver resulted in fungus growth and corrosion of PV cell interconnects. The fungus growth is inhibited when the receiver operates at high temperature.

The weather has improved significantly in 1983. The PV receivers appear to have reached a steady-state condition and no major degradation has been noticed over the last year of operation.

Despite the initial problems, the system is currently operating reliably. After 1.5 years of operation, the system is performing at 70 percent of the design prediction. The system is in a fully automatic condition and does not require any onsite operator; although grid transients cause occasional problems and trip the PCU.

DOE funds for the system operation have run out as of March 1, 1983 and Acurex is investigating alternate means to keep the project alive and operating.
PREPARATION OF TOPICAL REPORTS FOR RESIDENTIAL SYSTEM DESIGN

BY

THE AMERICAN INSTITUTE OF ARCHITECTS FOUNDATION

Contract No.: 50-5802

Program Manager: G.C. Royal

Contract Amount: $143,114

Contract Duration: May 1982 - May 1983

Program Description: The objective of this program is to transfer the technology developed during the past eight years of the National Photovoltaic Program through a set of topical reports on residential systems. Information is designed to form the basis of a library describing state-of-the-art understanding and is presented in a format that encourages use by architects, engineers and others interested in residential systems. The AIAF is providing input to three of the 14 topical reports. These efforts are directed toward preparation of the following:

- A catalog of existing design tools available for the architect, listing their properties, requirements and relative applicability;
- A survey of predesign issues that summarizes potential institutional barriers of which the A/E should be aware; and,
- A microcomputer program that generates electrical array circuits and physical module arrangements to satisfy system power and voltage as well as roof geometry.

Current Status: The major technical activity of this program has been completed. Final report drafts in each of the three task areas have been submitted to SNLA for review.

Key Results: The summary of design tools identifies currently available PV system analysis tools and describes their capabilities, limitations and recommended use. Concise summaries are given for system performance models as well as insolation and weather data, residential load data and economic models. Both manual and computerized formats are described. Each description contains input requirements, key assumptions, operating requirements, output results and vendor support. Annotated references are also given to enhance the reader's overall understanding of PV technology models.

The predesign issues to be addressed in order of importance to the designer are: utility interconnection; regulations; environmental health and safety; financing; and insurance, liabilities and warranties.

The connection between the residence and the utility is critical to both feasibility and design. PURPA was passed to facilitate and standardize the utility interconnection. Rate structures are an important element in determining economic feasibility.
Regulations address the residence as electrical generator and requirement for sunlight. Zoning is the primary method for assuring solar access. Article 690 proposed for the National Electrical Code addresses major areas of concern for Photovoltaics. Standards play a vital role in establishing a higher level of confidence in a new technology.

Most health and safety concerns can be adequately addressed through careful attention to design, i.e., "good engineering practice." Primary health and safety considerations fall into the categories of construction and maintenance, electric shock, and problems for fire fighters.

Financing problems should be minimal if photovoltaic technology establishes a good track record. Federal and state incentives programs, addressing income, property, and sales tax incentives, often do not specifically include photovoltaics but do not exclude them. Lenders must be reassured that photovoltaic systems will not over-improve residences, in effect pricing them out of their market.

Potential legal problems may also be avoided through careful forethought. Architects and engineers as representative of their clients should understand the legal distinctions between strict liability and express warranty or implied warranty. Insurance availability is not expected to be a problem.

The PRESTO program that generates electrical array circuits and module arrangements consists of input, electrical layout and output components. PRESTO parameters are input interactively and consist of commands and data values. The commands permit the user to input data values, calculate candidate electrical circuits, and layout candidate electrical circuits. Data values input to PRESTO include system power, PCU voltage, module power and voltage, module size, roof area and the distance between modules.

The electrical model accepts the input data, determines candidate series-parallel module circuit capable of satisfying the system requirements and determines the number of modules needed in the array. For each candidate array circuit PRESTO displays the number of modules connected in series, the number of series circuits connected in parallel, the actual array power and voltage, as well as total module area.

There are four layout models that each produce a rectangular array using rectangular modules, with not more than two dummy modules. Each layout model reserves module locations on the roof and assigns series connected modules in parallel circuits to these locations. The array layout models consider such factors as module aspect ratio, roof aspect ratio and bus location along the edges of the array in assigning module and source circuit locations.

PRESTO output consists of summary reports of array circuit parameters, array size, and number of modules. A schematic array circuit diagram and module arrangement is printed at the end of each layout.
PHOENIX SKY HARBOR AIRPORT
SOLAR PHOTOVOLTAIC CONCENTRATOR PROJECT

W. J. McGuirk
Project Manager
Arizona Public Service Company
P.O. Box 21666
Phoenix, Arizona 85036

ABSTRACT

This project, one of four concentrator system application experiments sponsored by DOE's PRDA-35 Program, first delivered solar generated electricity in April, 1982. The 225 peak kW array field is comprised of 80 Martin Marietta "first generation" passively cooled tracking arrays, which feed a Power Systems and Controls inverter. The a.c. power output is stepped up to 12.6 kV and fed directly into the APS power grid at the Airport site. The Martin concentrator module design is identical, with minor exceptions, to the hardware supplied to the 350 kW Saudi Arabian Village project under the SOLERAS Program. Each concentrator uses a Fresnel lens to focus energy (36X) on a 2.25 inch diameter silicon solar cell. A total of 272 lens-cell combinations are mounted onto a pedestal mounted, two-axis tracking array structure. The system was constructed at a cost of approximately four million dollars.

The initial operating experience has been generally favorable, although several problem areas have been identified. The first year's net a.c. energy production is expected to be about 200,000 kWh, about half the amount expected from predictive models. The most frequently occurring operational problems have been in the array tracker drive, inverter control, current-voltage testing, and module assembly subsystems. During the second operating year, the full-time two man operating crew will be removed from the site to see how the system behaves on its own.

Before completion of the DOE funded operation in June, 1984, data regarding array current-voltage performance degradation vs. time, washing cycle frequency, and component replacement frequency, in addition to energy production values, is expected to be recovered to enhance system evaluation.
Status Summary

ANALYSIS OF THE STOCHASTIC PROPERTIES OF PHOTOVOLTAIC ELECTRIC GENERATION ON THE OPERATION OF UTILITY SYSTEMS

P.M. Anderson Anjan Bose P.E. Russell D.K. Tice M.M. Khan
Arizona State University

The technical approach to this investigation is to evaluate the dynamic operation of electric utility systems through digital computer simulations. The simulation program used for this purpose is an existing code, developed by Systems Control, Inc. as part of a DOE research project. This code, referred to herein as AGCSIM, contains models of the power plants and the system control center, with these models designed to accurately compute the system control performance over a period of several minutes of time. The simulation is driven by the system load as a function of time, as shown in Figure 1. Computed outputs include the system frequency, generated power at each plant, tie line power between control areas, and certain control parameters.

The tasks defined for the project may be summarized as follows:

1. Simulation Installation and Validation
2. Generation Modeling
3. PV System Modeling
4. Load Modeling
5. Production Runs and Performance Evaluation

Progress on these tasks are summarized as follows:

1. Simulation Installation and Validation
   The simulation program was obtained from Systems Control, Inc. and installed on the ASU VAX 11/780 computer. A verification run confirmed that the code performed correctly with input data provided with the program.

   To validate the simulation, a test was performed to compare the simulation against the actual performance of the power system in Arizona. For this purpose, data was collected on load, generation schedules, and interconnection schedules for November 24, 1982 for systems owned and operated by Arizona Public Service Company and the Salt River Project. This required modeling the actual utility generating plants, the loads for each company, and the interchange schedules. The results of this step, now under active study, will be used to judge the adequacy of the simulation to perform the kind of analysis required for this project.

2. Generation Modeling
   In order to achieve realistic simulation results, the actual existing generation operated by APS and SRP will be used for all computation. This requires modeling the boiler-turbine-generator systems of these utilities in considerable detail.

   The boiler-turbine model is important in the dynamic analysis over a 0-30 minute time frame. This requires careful analysis of the thermal capacitance of the boiler fluid and the lags associated with the reheat turbine operation. The evaluation of these boiler-turbine constants requires the use of physical data on the physical parameters as well as operating characteristics of each boiler. These data have been obtained, with considerable help from the utilities, and the appropriate parameters evaluated.

3. PV System Modeling
   The PV system model is essentially a model of the change in PV output for various cloud conditions. Two models have been constructed: a deterministic model and a stochastic model. The deterministic model assumes a solid cloud front that gradually covers the PV array as a function of time, providing a sharp dip in PV generated power. The stochastic model assumes a random cloud distribution, which results in randomly varying power output. If the magnitude of these fast changes is large, it is of interest to see the effect this has on the overall system control.
4. Load Modeling
   As noted previously, a load profile of the APS and SRP systems is available for a specific day. However, it is important that consideration be given to various load profiles experienced by utilities in different seasons to see if any particular load profile is critical to the control problem. For this purpose, the Synthetic Utility System load data, published by EPRI, is used. This provides a wide range of load conditions for study, each of which can be evaluated for performance with and without PV generation.

5. Production Runs and Performance Evaluation
   This task will be pursued after the validation runs have been completed. The performance evaluation will be made using control performance parameters defined by the utility industry. These parameters include:
   - Area Control Error (ACE)
   - RMS value of ACE
   - Average ACE
   - Filtered ACE
   - Interchange Error
   - Inadvertent Energy
   - Time Error
   - RMS Frequency Deviation
   - Average Frequency Deviation
   - Time between Zero Crossings of ACE
   - Time between Zero Crossings of Frequency Deviation

We designate these as the Performance Tests. These Performance Tests will be scored for increasing levels of PV penetration until test failures begin to occur. These failures will be recorded and, if significant, will be evaluated for possible correction and improvement.
Commercial Application of a Photovoltaic Concentrator System (CAPVC)

W. R. Kauffman
The BDM Corporation
1801 Randolph Road, S.E.
Albuquerque, New Mexico

The BDM Corporation has completed the installation of its photovoltaic concentrator application experiment denoted as CAPVC (Commercial Application of a Photovoltaic Concentrator). The system was dedicated in July of 1982. This is a nominal 50 kilowatt peak system located on the roof of the BDM facilities in Albuquerque, New Mexico. The photovoltaic concentrating array is a single-axis linear parabolic trough utilizing single crystalline silicon photovoltaic cells under 41.56 suns of net solar concentration. A total of 7,560 square feet of aperture is provided by 54 Solar Kinetics T-700 7-foot aperture mirrors configured in nine north-south oriented rows. A two-piece 90° V-shape receiver places the cells at the focal point of the mirror and provides cooling utilizing an ethylene glycol/water mixture. The photovoltaic array is designed to operate in parallel with the local utility in an augmentary load sharing mode. A portion of the thermal energy resulting from the cell cooling is used for building heating during winter months.

The major subsystems of CAPVC are the photovoltaic array, DC and AC power conditioning, thermal system, and the control and data acquisition systems. The array is composed of the concentrating mirror, receiver tube and the PV-cell and module. The power conditioning includes the Westinghouse inverter and the wiring and switchgear. The thermal system involves both a heat rejection circuit and a building heating circuit utilizing ground coupled heat pumps. Components of the control and data acquisition system are the collector control loops and the instrumentation transducers. The overall control and safety monitoring of the system is accomplished automatically by an AIM-65 micro-computer. The controls and instrumentation equipment are located in a central monitoring area found near the building entrance for easy visitor access. The basis of the data acquisition system is a government furnished HP-9845 computer driven acquisition system.

The system is currently operating fully automatically 7 days a week including holidays. Final alignment of the photovoltaic receivers was completed in late March 1983 and it is expected that the system should perform near its design point during summer solstice. The remainder of the contract through December 1983 will involve day-to-day operation and maintenance with data acquisition by the HP-9845 and system evaluation by the BDM engineering support staff.

Initial operation of the array resulted in a slight discoloration and minor bubbling of the photovoltaic modules at design operating temperatures. This was observed during the first few weeks of operation and has not progressed since the original occurrence. Some module shorting to substrate has also occurred, but to date the use of spares and the repair of these modules has allowed a full complement of modules to remain in the field. It appears that ASEC did not properly isolate some of the internal wiring during the final assembly processes. Tracking with the Solar Kinetics shadow band trackers has been less than optimum and has been one of the major operational headaches. The mechanical portions of the system have operated well with only minor maintenance required. The entire mirror field was cleaned in January 1983 with a resulting substantial increase (20-30%) in power. Previous cleaning resulted in only 7-9% power increases; however, more attention will be paid to this area of operation and maintenance in the future.
Bechtel Group, Inc., under a contract with Sandia National Laboratories, is conducting a study of grounding and dc system fault protection in photovoltaic power systems. The emphasis of the study is on large (1 to 1000 MW) central station type plants with medium-sized (20 to 1000 kW) systems also addressed. In addition, United Technologies Corporation (UTC), under subcontract to Bechtel, is evaluating the requirements for PCS isolation transformers in medium-sized systems. UTC is also contributing to the grounding/fault protection study.

Current practices in other technologies and existing codes were reviewed for relevance and applicability to photovoltaic power plants. A set of design criteria was developed. Important among these criteria is the voltage limit allowable for possible personnel exposure during fault (and normal) conditions. This element of design along with requirements for operation of relaying require grounding and fault protection design to be considered simultaneously.

Evaluation of plant and system designs indicated that lightning protection and faults in the plant ac substation may influence grounding system design more than the dc system. The design of the grounding system is also strongly influenced by items beyond the control of the designer (e.g., soil resistivity). Overall costs can be reduced by integrating the grounding system with other plant subsystems. Examples of this are the use of rebar in concrete array foundations as ground rods, the use of foundation and wiring excavations to bury grounding cables, and the use of array structural elements (e.g., torque tubes in flat plate arrays) to form part of the ground system.

In the area of dc fault protection, a computer program was used to estimate fault current for postulated subfield and dc wiring configurations. Protection circuit configurations and equipment were evaluated. Surge protection and the interaction of the PCS were also evaluated. Vendors and manufacturers were contacted to catalog the characteristics of currently-available sensors and protective devices needed to meet system design requirements.
PHOTOVOLTAIC DATA REDUCTION CENTER

Operated by Boeing Computer Services
for Sandia National Laboratories

The Data Reduction Center system was designed to collect data from a large number of photovoltaic sites having a large variance in configuration and measurements. The data are archived on the Boeing Computer Services Mainstream EKS System where it can be made available to interested researchers. Monthly reports are produced for Sandia National Laboratories using selected data.

The Data Reduction Center has three main elements: On-Site Data Acquisition System (ODAS), Data Collection system (DCS), and the Data Archiving Analyis and Reporting System (DAARS).

The ODAS consists of a Hewlett-Packard 9845B computer system which processes data from a variety of measurement devices. The measurements are local weather data, solar radiation available, solar cell temperatures, voltage, and currents, and power conditioning unit parameters. ODAS acquires and displays data once every minute and averages and records data in 10 or 30 minute intervals. These data are stored on small tape cartridges for use by the site operators, contractors, and the BCS Data Collection System (DCS) in Seattle, Washington. Each night, when system activity is low, the DCS system calls the individual sites and requests the latest data files.

The DCS consists of a PDP 11/23 computer system with auto-dial capability and a RJE interface to the large scale Mainstream EKS system. The DCS system gathers data from the various sites and periodically sends it to the DAARS on the Mainstream EKS system. Some preliminary out-of-range determinations are done on the 11/23 computer.

The DAARS system is located on the Mainstream EKS facility located in Bellevue, Washington. This system evaluates all collected data statistically by measurement type and produces monthly reports for Sandia National Laboratories.

The DCS system capability has been improved, ODAS has been enhanced and DAARS has been improved over the original version. The system has now passed from the development phase to a production status. Some work is being done to improve efficiency and reduce costs but the system is now basically mature.

The quality of the data gathered is now of prime concern. There has been a program instituted to convey anomalies to Sandia National laboratories in a timely manner for appropriate action. A statistical data quality report was created to help in this effort. The statistical report gives minimum and maximum values for recorded data together with the mean, standard deviation and number of out of range samples.

At the present time data are being collected and analyzed from 9 sites. Six of the sites are flat plate collectors and are located in Beverly, Massachusetts, El Paso, Texas, Lovington, New Mexico, San Bernardino, California, Oklahoma City, Oklahoma, and Natural Bridges, Utah. Two of the sites are linear concentrator collectors and are located in Albuquerque, New Mexico, and Dallas, Texas. One site is a point concentrator and is located in Phoenix, Arizona.
PHOTOVOLTAIC SOUTHEAST RESIDENTIAL EXPERIMENT STATION (SE RES)

Contract Summary
Florida Solar Energy Center
and
Georgia Institute of Technology
April 1983

Project I.D. No.: DE-FC04-82AL20729 Amount: $2 million (DOE) + $1,323,296 (cost share)

Project Start Date: 30 September 1982 End Date: 30 September 1987
Project Managers: Gerard G. Ventre (FSEC), Sidney I. Firstman (GIT)
Principal Investigators: Gobind H. Atmaram (FSEC), Larry E. Banta (GIT)

Project Description

The Photovoltaic Southeast Residential Experiment Station (SE RES) is jointly operated by the Florida Solar Energy Center (FSEC) and the Georgia Institute of Technology (GIT). Operation of the five-year SE RES project began on 30 September 1982 with primary funding via a cooperative agreement with the U.S. Department of Energy Albuquerque Operations Office. Cooperating with FSEC and GIT on the project are the Alabama Solar Energy Center (ASEC) and several major utility companies in the southeast: Alabama Power Company, Florida Electric Power Coordinating Group, Florida Power and Light Company, Florida Power Corporation, Georgia Power Company, Jacksonville Electric Authority, Southern Company Services, Inc., Tampa Electric Company and the Tennessee Valley Authority.

Experiments to be conducted fall into two major categories: 1) system and subsystem evaluation and 2) utility grid-related experiments.

The system and subsystem experiments will utilize prototype systems at the FSEC primary site in Cape Canaveral, existing PV residential systems at various field sites throughout the Southeast and a flexible subsystem test facility at FSEC. These experiments are designed to:

- Characterize the solar and photovoltaic resource at representative field sites throughout the Southeast.
- Evaluate the long-term performance and reliability of residential photovoltaic systems using both side-by-side comparison at the primary site and existing photovoltaic residences throughout the Southeast which will be equipped with similar data acquisition equipment and instrumentation.
- Evaluate various modules, power conditioners and array mounting techniques under controlled conditions using the subsystem test facility.
- Identify subsystem failure mechanisms and report this information to manufacturers.
- Establish safety, maintenance and reliability requirements for photovoltaic system operation in a grid interactive mode.
- Verify predictive analytical models using measured system performance data.
- Develop residential building designs that not only reduce overall demand, but also provide for greater direct utilization of photovoltaic-generated electricity.

The grid-related experiments will focus initially on harmonics and fault protection and safety. Additional topics to be pursued include voltage regulation and reactive power compensation, isolated operation or islanding and analysis of the effects of widespread photovoltaics use on both distribution and grid system operations.
Status of Principal Tasks

1. Planning Reports

Three distinct planning reports are required project deliverables: a) an Organizational Management Plan, b) a Quality Assurance Control Plan and c) a Research Plan. All three tasks have been completed, most notably the Research Plan with an addendum listing DOE/Sandia comments and FSEC/GIT responses. The Research Plan will be reviewed and possibly revised in September 1983 and September 1984.

2. Prototype Development

Plans call for the construction at FSEC of three prototypes in 1983 and two in 1984. The design of the first three prototypes is in progress, construction should begin in May 1983 and be completed by October 1983. Tree-topping and land-clearing have been completed, modules and panels selected, and final design review scheduled for 15 April 1983. Table 1 below summarizes the important design characteristics of the three 1983 prototypes. All arrays will be tilted at 22.6° to the horizontal, which corresponds to a 5/12 roof pitch.

Construction of the three 1983 prototypes will take place simultaneously with FSEC acting as designer and general contractor.

3. Subsystem Test Facility

The FSEC subsystem test facility consists of a building structure with approximately 40 m² floor area and a roof slope of 6/12 or 26.6°, standoff mounting hardware which can accommodate a wide variety of module sizes, roof area for approximately 2 kWp array sizes, electrical wiring and couplings which allow for expeditious short-term testing of components and conditions, four two-axis tracking test stands (each capable of handling 400 Wp of subarrays) and a dual instrumentation system allowing for simultaneous testing of both fixed and tracking arrays. The subsystem facility is complete except for installation of one of the two instrumentation packages, and preliminary shakedown and checkout is underway.

The GIT test facility is being expanded from a 1 kWp to a 2.5 kWp rack-mounted array. The array powers a 4 kW Abacus Sunverter power conditioning unit through a relay switching system which allows easy substitution of other inverters.

4. Field Site Data Collection and Evaluation

Table 2 below shows the residential field sites that will be used to measure both resource and photovoltaic system performance at representative locations in the Southeast.

The FSEC PV house was recalibrated in February 1983 and two years of performance data have been reported.

5. Grid-Related Research

A number of meetings have been held with utility representatives and a preliminary statement of work was attached to the Research Plan in February 1983. More detailed specification of this predominantly utility cost-shared effort will continuously evolve.

6. Technology Transfer

The first meeting of the Consulting Committee was held at the Florida Solar Energy Center in November 1982. One practical photovoltaics workshop was held in January 1983 and a public seminar given in March 1983. A special photovoltaics technology and market projection workshop for government officials and a utilities conference have been scheduled for Spring 1983. Several publications and slide presentations are under development. Table 3 summarizes completed and planned programs.
Table 1. Characteristics of the Three SE RES Prototypes Planned for 1983

<table>
<thead>
<tr>
<th>No.</th>
<th>Module</th>
<th>Cell Material</th>
<th>Active Array Area</th>
<th>Array DC Power</th>
<th>Mounting</th>
<th>Inverter</th>
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<tbody>
<tr>
<td>1</td>
<td>(60) Photowatt</td>
<td>Single Crystal Czochralski</td>
<td>37m²</td>
<td>3kWp</td>
<td>Standoff</td>
<td>Alpha Energy Solar Inverter 3kW</td>
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<td></td>
<td>ML 7050</td>
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<td></td>
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<tr>
<td>2</td>
<td>(27) Mobil Ra 180</td>
<td>Single Crystal EFG Ribbon</td>
<td>58m²</td>
<td>4.4kWp</td>
<td>Integral</td>
<td>APCC Sunsine 4000 4kW</td>
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<tr>
<td>3</td>
<td>(70) Solarex PL 120</td>
<td>Polycrystalline</td>
<td>59m²</td>
<td>4.4kWp</td>
<td>Integral</td>
<td>Abacus Sunverter 4kW</td>
</tr>
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</table>

Table 2. Characteristics and Status of SE RES Field Residences/Sites

<table>
<thead>
<tr>
<th>Field Residence</th>
<th>City</th>
<th>Array DC Power</th>
<th>Mounting</th>
<th>Module</th>
<th>Inverter</th>
<th>Status</th>
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<tbody>
<tr>
<td>FSEC PV House</td>
<td>Cape Canaveral, FL</td>
<td>5kWp</td>
<td>Standoff</td>
<td>ARCO</td>
<td>Helionetics</td>
<td>Fully operational since December 1980</td>
</tr>
<tr>
<td>Tyndall AFB</td>
<td>Panama City, FL</td>
<td>2kWp</td>
<td>Standoff</td>
<td>ARCO</td>
<td>Windworks</td>
<td>Instrumentation being upgraded</td>
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<tr>
<td>Georgia Power House</td>
<td>Atlanta, GA</td>
<td>4kWp</td>
<td>Integral</td>
<td>Solec</td>
<td>Helionetics</td>
<td>Fully operational since Fall 1982</td>
</tr>
<tr>
<td>ASEC PV Test Facility</td>
<td>Huntsville, AL</td>
<td>2.2kWp</td>
<td>Standoff</td>
<td>ARCO</td>
<td>Helionetics, APCC and Windworks</td>
<td>Start-up in March 1983</td>
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<td>TVA 1</td>
<td>Chattanooga, TN</td>
<td>4kWp</td>
<td>Standoff</td>
<td>Solarex</td>
<td>Abacus</td>
<td>PV system being installed</td>
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<td>TVA 2</td>
<td>Chattanooga, TN</td>
<td>4kWp</td>
<td>Modified- Direct</td>
<td>Solarex</td>
<td>APCC</td>
<td>PV system being installed</td>
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<td>TVA 3</td>
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<td>4kWp</td>
<td>Standoff</td>
<td>TBD</td>
<td>TBD</td>
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<td>TVA 4</td>
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<td>Integral</td>
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<td>FPL</td>
<td>Miami, FL</td>
<td>10kWp</td>
<td>TBD</td>
<td>TBD</td>
<td>TBD</td>
<td>System not built</td>
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Table 3. Completed and Planned Technology Transfer Programs

<table>
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<tr>
<th>Program Title</th>
<th>Type</th>
<th>Sponsor</th>
<th>Date(s)</th>
<th>Audience</th>
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<tr>
<td>Utilities Research Group Meeting</td>
<td>1-day meeting</td>
<td>GIT</td>
<td>October 26, 1982</td>
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<tr>
<td>Utilities Research Group Meeting</td>
<td>2-day meeting</td>
<td>GIT/GPC</td>
<td>November 9-10, 1982</td>
<td>Utilities</td>
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<tr>
<td>Consulting Committee Meeting</td>
<td>1-day meeting</td>
<td>FSEC/GIT</td>
<td>November 22, 1982</td>
<td>Industry</td>
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<tr>
<td>Practical Photovoltaics</td>
<td>1-day short course</td>
<td>FSEC</td>
<td>January 27, 1983</td>
<td>Industry</td>
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<tr>
<td>Utilities Research Group Meeting</td>
<td>2-day meeting</td>
<td>GIT/FPL</td>
<td>February 8-9, 1983</td>
<td>Utilities</td>
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<tr>
<td>PV Technology and Markets</td>
<td>90-minute seminar</td>
<td>FSEC</td>
<td>March 7, 1983</td>
<td>Public</td>
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<tr>
<td>PV Technology and Markets*</td>
<td>1-day workshop</td>
<td>FSEC</td>
<td>April 25, 1983</td>
<td>Government Officials</td>
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<tr>
<td>Practical Photovoltaics*</td>
<td>1-day short course</td>
<td>FSEC</td>
<td>April 28, 1983</td>
<td>Industry</td>
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<tr>
<td>Utilities Research Conference*</td>
<td>2-day workshop</td>
<td>GIT</td>
<td>May 3-5, 1983</td>
<td>Utilities</td>
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</table>

*Planned programs
DEVELOPMENT OF A UNIQUE UTILITY INTERACTIVE POWER CONVERSION UNIT

Larry R. Suelzle
Helionetics, Inc.
17312 Eastman St.
Irvine, CA 92714

For the past two years, Helionetics' DECC Division has been actively involved in the development of a low cost Utility Interactive Power Conversion Unit for use with alternate energy sources, including rooftop sized photovoltaic array. This development, partially funded by the U.S. Department of Energy, is based on the patented DECC Class-D Amplifier. The following narrative and figures are a statement of progress and accomplishment of this effort.

THE PROGRAM

The program was divided into 8 tasks or areas of concentration. During the initial optimization Task 1 the existing amplifier design was refined. Trade-offs between cost, efficiency, performance, size and weight were studied. Task 2 was the construction of a 5 kW brassboard converter in accordance with the design developed in Task 1. Task 3 was the testing of the brassboard converter built in Task 2. Task 4 was the design of a complete prototype 5 kw converter, based on the original optimization results from Task 1 and the results of the tests performed on the brassboard converter in Task 3. Task 5 consisted of building three 5 kW prototypes of the converter using the design resulting from Task 4. Task 6 was the preparation of a test plan to demonstrate the capabilities of the prototype converters, including performance in environment extremes. Task 7 will consist of testing the prototypes built in Task 5 in accordance with the test procedure developed in Task 6. Task 8 will consist of evaluation of the results of Tasks 1-7 and a publication of a report summarizing the program.

THE TECHNOLOGY

The converter utilizes a patented Class-D Amplifier. The degree of control attained in the circuitry allows the inverter to operate stably between a non-ideal source and a non-ideal utility grid. The advantages of the DECC inverter approach are listed below:

(1) Use of a wide-band amplifier in the converter allows the converter to respond advantageously to both transients and harmonics.

(2) The control scheme for the converter allows control of both the output power and the output power factor. The converter will track the peak power of a non-ideal source, such as is provided by a photovoltaic array. The output power factor is controlled so that the converter always supplies only real power.
to the grid. Alternatively, it can be controlled to help "level" the utility grid by providing reactive power during negative transients in the utility voltage, and absorbing reactive power during positive transients of the utility voltage.

The converter, inherently acts as a frequency translator, converting harmonics present on the utility grid to useful power at the primary grid frequency.

The control scheme for the converter utilizes linear voltage feedback around the power conversion stage which consists of a switching-mode linear power amplifier and a series output inductance. The attenuation and phase characteristics of the feedback loop are chosen and controlled to produce a negative output impedance at the fundamental output frequency (60 Hz), and a positive output impedance at frequencies from 100 to 1000 Hz. Power is therefore supplied (to the grid) at 60 Hz, while being extracted from harmonic, transient, and noise voltage on the utility grid. Since the power conversion circuitry is essentially non-dissipative, the extracted power is available for re-conversion to output power at the fundamental frequency.

Although the first-generation inverters will be built using discrete components, sufficient flexibility will be maintained in the design so that future, mass-produced inverters can incorporate microprocessor or Large Scale Integration (LSI) control electronics, with a consequent reduction in production costs.

THE PROGRESS

The program has progressed to the completion of Task 5, the building of the three prototypes. The next part of the program is to test the prototypes (Task 7) to a (Task 6) test plan. The final report (Task 8) will bring the program to end.
LOVINGTON SQUARE SHOPPING CENTER PHOTOVOLTAIC SYSTEM

Lea County Electric Cooperative, Incorporated
P.O. Box 1147
Lovington, New Mexico 87260

Program Manager: Pete Felfe
(505) 396-3631
Contract No.: #DE-AC04-79ET20628
Contract Amount: $225,000 (Phase III)
Contract Duration: May 19, 1981, to May 19, 1983

Project Description: This contract is for the operation and maintenance of the 100-kilowatt photovoltaic system in Lovington, New Mexico. The system has been operational since March 17, 1981, and has produced more than 375 megawatt hours of energy in the first two years. This provides about 8 percent of the annual electrical energy requirements of the Lovington Square Shopping Center.

Current Status: The Lea County Electric Cooperative is operating and maintaining the system, with the New Mexico Solar Energy Institute providing some technical support. Data analysis will continue through the Phase III contract.

Key Results: This system site is not manned and the photovoltaic system operates automatically. Reliability of prime system equipment has been high, with few actual hardware failures. However, frequent "resets" of the power conditioning units and the data acquisition system have been necessary. A daily site visit is made to check system status. Actual maintenance time, including site visits, has averaged 1.7 hours per megawatt hour of production.
Feasibility of a photovoltaic central power station application has been addressed by a variety of system designers, utility planners, and economic analysts. 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 done under this contract was to: build on these past results, refine the requirements to specific design criteria; produce detailed reference designs for both flat-plate and concentrator-array photovoltaic central power stations at an actual utility owned site.

Martin Marietta in conjunction with Arizona Public Service and Stearns Roger Corporation as subcontractors have completed the task to develop a preliminary design of a photovoltaic central power station (CPS) at Arizona Public Service's Saguaro Power Plant.

Results of these tasks have been reported as follows:

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

Configuration is a 100 MWe plant subdivided into modular blocks of 5 MW each, no storage. Each of the 5 MW array subfields contains one 5 MVA inverter. Field DC voltage is ±1000 VDC with subfield AC output 34.5KV.

For the flat-plate design, a 1.32 m x 1.32 m, 178.8 Wp glass covered aluminum framed module containing dendritic web cells was chosen for use in the flat-plate array. This module utilized poly-crystalline ribbon cells with an assumed power conversion efficiency of 14.2%. A panel was defined as the smallest field installable component consisting of eighteen modules. To complete the 100 MWe field, 45,000 panels would be organized into twenty, 5 MWe subfields each with an individual inverter. The total land requirements for the flat plate CPS is 1.56 square miles. The array field area requires 1.35 square miles. Based on Phoenix, Arizona, SOLMET-TMY data the estimated annual energy output is predicted to be 247 GWh.

In the case of the concentrator, Martin Marietta's second generation array was chosen due to the maturity of the design and the fact that over 500 kW of an earlier similar design had already been installed. The array field consists of 22,000 arrays. Each array contains sixty modules measuring 0.43 meters by 1.47 meters in length. As with the flat plate design, there are twenty subfields containing 1100 arrays each. This concentrating module utilizes a concentration of 100 suns using a 2.67 square centimeter silicon float zone solar cell. The module has an assumed power conversion efficiency of 19.3%. Total land area required is 2.28 square miles. Annual output is predicted to be 284 GWh.

In summary, the utility recommendations for future work identified several important areas: economic issues; the capability of inverters; the fact that straight PV has a poor fit with the utility grid system load; and APS's future generation mix will have a significant preponderance of coal and nuclear, working to the disadvantage of photovoltaics. Even with these disadvantages, however, it is believed that PV central power stations can be of value to utilities in the Southwestern U.S. if the costs come down as projected.
The Southwest Residential Experiment Station (SW RES) has been in existence since September 1980. The first of eight FY81 prototype residential photovoltaic (PV) systems was activated in March 1981; the last in September of that year. Since that March 1981 event, the eight prototypes have produced more than 90 megawatt hours of rooftop-generated energy; some reliably, some not.

The goal of the SW RES is, broadly, to foster the early implementation of grid-connected residential PV systems. More specifically, our charter is to identify and resolve those technical and institutional issues that will influence widespread adoption of such systems. To fulfill this charter, the SW RES staff are involved in a variety of efforts beyond the prototype evaluation effort. Current activities include the fine-grained monitoring of five Las Cruces residences (non-PV); similar monitoring of two Las Cruces utility feeders (one of which serves the SW RES site and undergoes near-daily reverse power flow); and monitoring, via stand-alone data acquisition systems, grid-connected PV residences in Santa Fe, New Mexico, and Yuma, Arizona. We are involved, through work of the staff and feedback from the SW RES Consulting Committee, in institutional issues such as financing, insurance, codes, and utility-interconnection questions. Through publications, on-site visits, workshops, technical papers, and periodic data reports, we are sharing data, results, and conclusions with the public, the PV community, and the National Photovoltaic Program management.

Key results can be briefly stated: we see no significant technical barriers to grid-connected residential PV systems. Similarly, save the apparently-unsettled PURPA (Public Utility Regulatory Policies Act) issue, we foresee no major institutional barriers. Economic issues are still of paramount importance. It appears that value (to the homeowner) of roof-mounted energy will vary from state to state as a consequence of the state's PURPA implementations; this will probably strongly affect rate of implementation from one state to another.

There are many areas where technical questions remain. Some modules have failed, and the root causes are not yet known in all cases. Our second-generation inverters have been flawless and for the past six months all first-generation units have also been reliable, but high efficiency units at lower cost must be developed. We have many questions regarding array thermal behavior and are working to develop a better understanding of thermal phenomena. We have observed a fairly uniform shortfall between predicted and actual energy production performance of all FY81 prototypes and are evaluating data to identify reasons for this phenomenon.
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

CURRENT ACTIVITIES

Monitoring Prototype Performance
Monitoring Five Non-PV Residences
Monitoring Two PV Residences
Studying PV/Utility Interface
Issuing Data and Information
Planning "Flexible" Prototype
Ninth Prototype In Works

APRIL 14, 1983
## CHARACTERISTICS, FY81 PROTOTYPES

<table>
<thead>
<tr>
<th>PROTOTYPE SYSTEM</th>
<th>MODULE SUPPLIER</th>
<th>ARRAY AREA (m²)</th>
<th>ARRAY PEAK POWER (kwp)</th>
<th>MOUNTING METHOD</th>
<th>ARRAY TILT (°)</th>
<th>INVERTER SIZE</th>
<th>INVERTER SUPPLIER</th>
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<tr>
<td>ARCO Solar</td>
<td>ARCO Solar</td>
<td>88.2</td>
<td>7.4</td>
<td>Direct</td>
<td>25</td>
<td>8 kw</td>
<td>Windworks</td>
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<td>6 kw</td>
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<td>General Electric</td>
<td>General Electric</td>
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<td>6.7</td>
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<td>30</td>
<td>6 kva</td>
<td>Abacus</td>
</tr>
</tbody>
</table>

*Replacement Inverter

**April 14, 1983**
### SOUTHWEST RESIDENTIAL EXPERIMENT STATION—RESULTS AND ISSUES

#### PROTOTYPE PERFORMANCE

<table>
<thead>
<tr>
<th>System</th>
<th>Days Down</th>
<th>Capacity Factor (%)</th>
<th>Actual/Predicted (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCO</td>
<td>0</td>
<td>16.2</td>
<td>92.5</td>
</tr>
<tr>
<td>ARTU</td>
<td>0</td>
<td>17.5</td>
<td>82.0</td>
</tr>
<tr>
<td>BDM</td>
<td>0</td>
<td>17.5</td>
<td>78.2</td>
</tr>
<tr>
<td>GE</td>
<td>27</td>
<td>13.4</td>
<td>69.2</td>
</tr>
<tr>
<td>SX</td>
<td>30</td>
<td>12.1</td>
<td>42.8</td>
</tr>
<tr>
<td>TEA</td>
<td>1</td>
<td>17.2</td>
<td>86.9</td>
</tr>
<tr>
<td>TSC</td>
<td>11</td>
<td>18.5</td>
<td>68.6</td>
</tr>
<tr>
<td>WST</td>
<td>7</td>
<td>15.8</td>
<td>61.0</td>
</tr>
</tbody>
</table>

JUNE 82 - MARCH 83

CY 1982

APRIL 14, 1983
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

FAILURES, PROBLEMS, AND CURES

Major Abacus Fix May 18-20, 1982
High Site Line Voltage (DECC, APC, ARTU)
ARTU Isolation Transformer
Loosening power connections - SX Abacus
ARCO Module & Wiring Shorts
Solarex Modules - 5 Discovered October 8, 1982
GE Shingles - Problem Surfaced November 11, 1982
Loosening power connections - TSC Gemini - October 12, 1982
TSC Gemini Failure July 13-15, 1982
SOUTHWEST RESIDENTIAL EXPERIMENT STATION--RESULTS AND ISSUES

ADDITIONAL PROTOTYPE USING RIBBON TECHNOLOGY

FP Mailed May 14, 1982
Three Proposals Received June 15
Selection June 16: Mobil Solar Energy
Contract Awarded August 1
Preproduction Modules September 22 - BAD NEWS
Delay Granted, September 27
CDR Held March 21
Prototype Acceptance Late June 1983
THE NEWMAN POWER SYSTEM PHOTOVOLTAIC PROJECT

New Mexico Solar Energy Institute
New Mexico State University
Box 3 SOL
Las Cruces, New Mexico 88003

Program Manager: V. Vernon Risser
(505) 646-3948
Contract No.: DE-AC04-81AL17093
Contract Amount: $233,082 (Phase III)
Contract Duration: July 1, 1981, to June 1, 1983

Project Description: This contract, the third phase of the program funded by the Department of Energy to design, build, and test photovoltaic (PV) systems, has covered the operation, data acquisition and analysis, and maintenance of the 17.6-kilowatt system in El Paso, Texas. The power generated displaces rectified ac power used by generator control equipment tied to an uninterruptible power supply (UPS). The operating voltage of the UPS, 134 volts dc, controls the voltage of the ungrounded PV system. The PV array has 64 panels of 9 series-connected modules. The 64 panels are connected in parallel and are tied to the UPS through a dc switchboard that controls the daily sequencing of the system.

Current Status: The system has operated successfully for the past two years, producing more than 60 megawatt hours of energy. At the conclusion of this contract, the system will be operated and maintained by the site owner, El Paso Electric Company.

Key Results: The success of this project has demonstrated that intermediate-sized PV systems are technically feasible. They can be built and operated by personnel with no prior PV experience. They can be designed for unattended operation, and high reliability of prime system components can be expected.
PRINCIPAL CONTRACT

DYNAMIC SIMULATION OF DISPERSED, GRID CONNECTED
PHOTOVOLTAIC POWER SYSTEMS

BY

School of Electrical and Computer Engineering
Purdue University, West Lafayette IN 47906

Principal Investigators:
P.C. Krause
(317) 494-3481
O. Waszynzuk
(317) 494-3475

Contract amount: $449,986
Contract duration: May 1981 to December 1983

Project Description: The primary objective of this contract was to determine and evaluate the dynamic electrical behavior of dispersed, grid connected photovoltaic (PV) power generation. This includes the characterization of the individual PV system response at the secondary distribution level, the determination of the overall grid response with dispersed PV generation and the determination of the collective effects of PV generation at the transmission level. The project was divided into four tasks.

The primary objective of the first task was to develop appropriate dynamic computer models of a set of representative photovoltaic power systems. The systems studied include single and three phase, line and self commutated inverters. The second task involved the incorporation of these inverter models into detailed representations of representative distribution network configurations. Transient conditions studied include inverter startup, induction motor (load) switching, feeder faults, feeder tripping and reclosure, etc. The third task involved the determination of the collective effects of dispersed PV generation at the transmission level. An important part of this work involved the development of simplified PV system representations. Interpretation of results and reporting made up the fourth task.

Current Status: Detailed computer representations of a set of four PV systems have been developed and evaluated. The first report (SAND82-7160) which addresses simulation and control methodologies, has been written, reviewed and a final version recently submitted. A draft report addressing the results of the system studies has been written and submitted to Sandia for review. Additional work involving experimental verification of the computer models and further studies involving PCU malfunctions have recently been initiated.

Key Results: During the course of the studies, it was discovered that the controls for the self commutated systems exhibited unstable behavior during certain operating conditions. A new control system has been developed and evaluated. These controls are currently being constructed to be retrofitted into an existing inverter for experimental verification. In addition, it was discovered that the perturb and observe method of power tracking was unable to track peak power conditions whenever the insolation varied randomly as a result of cloud cover. A method of power tracking with improved dynamic performance has been developed and evaluated. Studies have indicated that the dynamic interactions between neighboring single phase PV systems are relatively minor, occurring in systems with a low short-circuit ratio (<5.0). The nature of these interactions is the subject of ongoing research. In the case of the three phase systems, the line and self commutated systems were able to withstand most test disturbances without failure and with relatively short recovery times. Aside from the potential of commutation failure, the LCI systems appeared to be least sensitive to utility disturbances. The sensitivity of the self commutated systems, which is attributed to the use of discrete patterns to regulate a weak source, can likely be reduced by improved inverter control techniques. Present research is focused on experimental verification of the computer models developed as part of this work.
The first year of the Phase III contract on "Operation and Evaluation" was completed on November 30, 1982. System performance during this year is summarized in Figure 1, which compares the actual monthly AC energy outputs with the amounts predicted from a computer simulation based on the SOLMET TMY weather data tape for Boston. Those months which show significantly lower output than predicted correspond to periods when system downtime was excessive due to various fault conditions which trip off the inverters.

The two DECC inverters (Helionetics, Inc.) which control the system operation are designed to shut down automatically upon detection of any one of twelve different fault conditions. In each case the inverter will remain shut down until manually

![Figure 1. AC System Output. Numbers along abissa are the number of days included in each month based on dates between meter readings.](image-url)
reset. Prior to the period shown (Figure 1), and through December of 1981, sporadic ground faults were the main cause of fault shutdowns as described at the previous (Third) Project Integration Meeting. After reducing the ground fault sensitivity in mid January, these sporadic ground faults were no longer a problem. But during January and February the system was plagued by shutdowns due to synchronization errors. These were caused by control circuits going out of range in cold weather. The problem was cured by replacing the temperature-sensitive components on the PC boards in early March. The system was essentially free of fault shutdowns during March and April, but a major malfunction of the computerized data acquisition system (ODAS) caused a series of ground fault shutdowns in May. These ended when the ODAS was disconnected and sent out for repair. In June, one inverter began to blow fuses due to an intermittent problem in one or two of the inverter legs, resulting in one half of the system being down for most of the month. This problem also occurred once in July. A number of shutdowns due to excessive grid voltage also occurred throughout one week in July. These ended when the utility fixed the voltage regulator at its substation (we were the only ones to let them know they had a problem). A few shutdowns due to overtemperature also occurred in July because the ventilation system in the inverter house had not been working properly. August was relatively free of fault shutdowns, but shutdowns of one inverter due to logic power errors began to occur frequently in September. A dirty pot in the bias power supply which feeds the control circuitry was causing the problem, which disappeared after the pot was cleaned in early October.

Both inverters were given a complete checkout and tuneup by the manufacturer in early October. Since then, fault shutdowns have been very rare and have not caused any significant downtime up to the present (a period of six months). For the full year shown in Figure 1, total system output was 78% of the predicted value. The shortfall can be accounted for entirely by the downtime caused by the various fault shutdown problems described. Based on the essentially fault-free operation over the past six months, these problems now appear to be behind us.
HIGH FREQUENCY LINK 4kW PHOTOVOLTAIC INVERTER FOR UTILITY INTERFACE

by

Alan Cocconi, Slobodan Cuk, and R.D. Middlebrook
TESLAco
490 South Rosemead Blvd.
Suite 6
Pasadena, California 91107

ABSTRACT

An advanced power conversion concept based on high frequency link is developed by TESLAco to generate a low cost, compact, photovoltaic to utility interface at the residential power level of 4kW. A single quadrant, dc isolated push-pull buck converter switching at 20kHz is used to generate a full wave rectified sine wave which is subsequently unfolded by a low speed four transistor bridge to result in 60Hz sine wave power output. A control strategy optimizing the output impedance of the inverter for the direct interface to the stiff utility voltage has been developed. Advanced peak power tracking circuitry continuously follows the peak power without operating point dither. Despite its state-of-the-art low weight of only 38 lbs., the inverter is 92% efficient.
During 1977, the MIT Lincoln Laboratory and the Agricultural Engineering Department, IANR, University of Nebraska, Lincoln, installed a 25 kW PV array at the UNL Field Laboratory at Mead, Nebraska. This was the first large PV array and consists of Solarex and Sensor Technology modules. The array has been utilized for research programs which have included the development of an automated irrigation system for 80 acres of corn, a natural-air grain drying system and an electric-arc process for producing nitrogen fertilizer, the latter in cooperation with Kettering Foundation Laboratories. Also developed at or immediately adjacent to the PV site are a 5 kW wind generator, a 13 kW cogenerator powered by methane from swine waste, a swine facility with both active and passive solar collectors and a 25 gal/hr alcohol still utilizing sweet sorghum.

Since 1977, data has been collected on the completely instrumented solar system. A 20 hp DC motor and 10, 15 and 20 hp AC motors were used to drive the surface irrigation system. Relative efficiencies, battery storage requirements, and operational characteristics were evaluated. Grain drying and nitrogen generator experiments were also conducted. Important operational concerns such as load matching, battery storage, power conditioning, array dirt accumulation, module failures and safety were investigated. Several publications have been written relating to agricultural applications as well as to the specific and overall performance of the PV system.

Sandia National Labs have provided funding for the Mead array since the Massachusetts Institute of Technology's Lincoln Lab withdrew from the field of solar energy in 1982. The one year Sandia contract which terminates on April 15, 1983, was intended to cover the minimal expenses required to maintain the solar site in operating condition and to maintain continuous acquisition of reliable performance data. Volt-ampere tests, battery equalization, array angle adjustment, and module cleaning are examples of regular maintenance procedures.

The University of Nebraska is interested in continuing the Mead solar site operation and data collection. The Agricultural Engineering Department has a particular interest at this time in the interfacing of the various power sources into a self-sufficient internal grid to power all farmstead needs including livestock housing, feed processing, grain drying and domestic power. However, future funding for the Mead site has not been secured as of this date.
IMPACT OF RESIDENTIAL UTILITY-INTERACTIVE
PHOTOVOLTAIC POWER SYSTEMS ON
THE UTILITY

by

University of Texas at Arlington
Arlington, Texas 76019

Principal Investigator: Jack Fitz
(817) 273-2268
Contract No: 58-5811
Contract Amount: $79,748
Contract Duration: June 1982 - August 1983

Project Description: This project investigates the effects of residential utility-interactive PV power systems on the distribution feeder. The following effects are considered:
* The effects of the PV inverter power and reactive power on voltage regulation
* The effects of PV inverter harmonic currents on the feeder
* The effects of a single PV power system on the distribution service transformer and on the customers served by that transformer

Current Status: Computer programs have been developed to evaluate the effects of the fundamental and harmonic components of inverter currents on the distribution feeder. A suburban feeder and a long rural feeder have been instrumented to obtain daily records of power, reactive power and voltage. Preliminary results are available for the suburban feeder.

A time-domain computer simulation program has been developed to simulate the non-linear magnetic characteristics of the service transformer, inverter waveforms and the customer loads. Both waveforms and harmonic content are obtained.

Key Results: Preliminary results for a suburban feeder indicate that residential PV power systems will not present a problem in terms of voltage regulation or harmonics on this feeder. This is based on the assumption that 20% of the homes have PV systems.
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