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Southeast Regional Experiment Station

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1. PROJECT OVERVIEW

1.1 Program Description

The Florida Solar Energy Center (FSEC), a research institute of the University of Central Florida (UCF), has operated the Southeast Regional Experiment Station (SE RES) for the U.S. Department of Energy (DOE) since September 1982. Sandia National Laboratories, Albuquerque (SNLA) provides technical program direction for both the SE RES and the Southwest Regional Experiment Station (SW RES) located at the Southwest Technology Development Institute at Las Cruces, New Mexico. This cooperative effort serves a critical role in the national photovoltaic program by conducting system evaluations, design assistance and technology transfer to enhance the cost-effective utilization and development of photovoltaic technology.

Initially, the research focus of the SE RES program centered on utility-connected PV systems and associated issues. The SE RES Utilities Research Group (URG) was established to support the national program and the SE RES from the utilities' perspective. Three utility-interactive residential prototype systems and a flexible test facility were designed and constructed at the SE RES to examine the performance of different PV arrays, power conditioning devices and balance-of-system components in Florida's hot, humid, salt-air environment. Four computer-controlled two-axis tracking arrays were also installed to investigate the seasonal and annual energy enhancement of different tracking modes in the southeast climate for flat-plate arrays.

In 1987, the SE RES began evaluating amorphous silicon (a-Si) thin-film PV modules for application in utility-interactive systems. The results of this work were applied to a joint project between the Florida Power Corporation (FPC), SE RES, SNLA and the Electric Power Research Institute (EPRI) in the design and installation of Solar Progress, a 15 kWp a-Si utility-interactive system in Orlando, Florida. Solar Progress, once the third largest a-Si PV system in the U.S. and provided valuable information regarding the design, installation, and operational performance of PV systems to the electric utilities.

Stand-alone PV systems began receiving increased emphasis at the SE RES in 1986. Research projects were initiated that involved evaluation of vaccine refrigeration, water pumping and other stand-alone power systems. The refrigerator systems evaluations supported the Central American Health Clinic Project, a cooperative effort between the DOE, SNLA, SE RES, the Organization of American States (OAS), and the Pan American Health Organization (PAHO). The goal of the project was to improve the reliability of health care through the use of PV technology. The PV water pumping research included evaluation of system design strategies and characterization of commercially available components. The results of this work have led to design optimization techniques and procedures for the sizing and modelling of PV water pumping systems.

Later recent research at the SE RES included test and evaluation of batteries and charge controllers for stand-alone PV system applications. The objectives were to gain a better understanding of charge controller and battery subsystem interactions and, ultimately to improve long-term component and system reliability and performance.

The SE RES project provided the foundation on which FSEC achieved national recognition for its expertise in PV systems research and related technology transfer programs. The State of Florida, utilities and private industry have all relied on this expertise to help them effectively implement the technology. The Florida Photovoltaic Systems Design Assistance and Training Center, sponsored by the Florida Governor's Energy Office, provided FSEC with the program support to package the research from the SE RES project and disseminate the results to the PV industry, utilities and educators through PV workshops. System design and procurement assistance was also provided to utilities, government agencies and others to aid in a successful track record of PV systems performance. These synergistic products of the SE RES illustrate the high visibility and contributions the FSEC PV program offers to the DOE.

1.2 SE RES Project Budget History

The original cooperative agreement for the SE RES covered the period from 9-30-82 to 3-14-85. However, through 1990, twelve (12) amendments and/or modifications to the contract were made to include new and revised statements of work. Approximately 70% of the DOE funding was matched with cost share from UCF/FSEC and other SE RES participants. An average overhead rate of 51% was assessed by UCF/FSEC on the contracts. This low overhead rate, and the high cost share percentage made the SE RES program an economical and effective means of accomplishing DOE's photovoltaic program goals.

Table 1 shows the breakdown of DOE and non-DOE funding for the SE RES project since the original cooperative agreement in 1982.

2. GOALS, OBJECTIVES AND ACCOMPLISHMENTS

This section describes the major program areas at the SE RES, including goals, objectives and significant results.

2.1 Systems Development and Evaluation

2.1.1 Prototype Systems, Flexible Test Facility and Tracking Array Field

Goals:

Assess the long-term performance of PV systems in Florida's hot, humid, salt-air environment to positively affect product development, system design, installation and operational procedures. Develop electrical and mechanical design guidelines.

Objectives:

1. Investigate long-term performance and reliability concerns of grid-interactive systems in the southeast region.

2. Assess the performance of different tracking modes in the southeast region.

3. Evaluate power conditioning equipment and other BOS components for residential utility-interactive systems.

Accomplishments:

1. Monthly performance reports were provided for the SE RES prototype utility-interactive residential systems and tracking array field for the period 1983 to 1989. The reports presented energy parameters, and significant events for the various system configurations and operational modes.

2. Crystalline silicon arrays at the SE RES showed high reliability over the first ten years of operation. None of the arrays showed significant power degradation.

3. Modules operated with a high degree of mechanical reliability. Junction box and interconnect design problems, identified at the SE RES, have encouraged the industry to produce new and improved designs.

4. Module current mismatch and losses in wiring, fuses, switches and diodes reduced system output approximately 10% below the performance expected from module specifications.

5. With few exceptions, self-commutated power conditioning equipment for utility-connected

residential applications in the 2 to 6 kW size demonstrated high reliability and conversion efficiencies in the 90% range. The possibility of islanding (continued inverter operation after loss of utility power) was minimal for most inverters and the inclusion of under/over frequency relays reduced the islanding potential with other inverters.

6. Stand-off array mounts eliminated concerns associated with integral mounts due to water leakage, higher operating temperatures and the need for precision mechanical designs. Based on the MIT design, a building block approach for roof mounted residential arrays was successfully used at the SE RES with modifications for the high wind load potential and corrosion concerns in Florida. Over a 50% reduction in array BOS and installation costs were achieved.

7. Computer controlled tracking arrays were more accurate than active sun sensing methods in the southeast climate. Two-axis tracking yielded 40% dc energy enhancement and single-axis tracking yielded over 20% dc energy enhancement, in comparison to an array at fixed latitude tilt in Cape Canaveral, Florida.

8. A unique 24-channel capacitive-loading I-V curve tracer was developed to perform continuous and automated PV module measurements and data storage. This system measured the long-term electrical performance of a-Si thin-film modules.

9. The anisotropic radiation model developed by Perez was used to accurately predict irradiance on tilted and tracking surfaces to within 3%. PVFORM, a PV simulation program developed at SNLA that utilizes the Perez model, slightly underpredicted system energy output on clear days and slightly overpredicted energy output on cloudy and overcast days.

2.1.2 PV-Powered Vaccine Refrigeration Systems

Goals:

Assess the performance, reliability and economics of vaccine refrigeration systems to positively impact the World Health Organization cold chain programs through improved design practices and implementation of large numbers of PV-powered systems.

Objectives:

1. Evaluate refrigerator/freezer thermal performance in terms of maintaining satisfactory operating temperatures under varying ambient temperatures, ice production levels and extreme use conditions.

2. Evaluate refrigerator/freezer electrical performance in terms of daily, seasonal and annual energy consumption for varying ambient temperatures, ice production levels, extreme use conditions and available solar resource.

3. Evaluate performance of the PV systems including the array, charge controller and battery subsystem characteristics with regard to optimal system design, sizing and operational procedures.

4. Develop analytical models of electrical and thermal performance of PV-powered vaccine refrigeration systems and verify these models with experimental data.

Accomplishments:

1. Three commercially available PV-powered vaccine refrigeration systems and a common kerosene unit were evaluated. A data acquisition system monitored the electrical and thermal performance of the systems.

2. Six pilot vaccine refrigeration systems were installed at Central American health clinics in 1987 two each in Guatemala, Honduras and El Salvador.

3. Monthly reports provided results of testing to the PV industry, government and user sectors from 1987 to 1990. Measured heat transfer coefficients, ice making capabilities and energy consumption for the three systems were presented.

4. Results were presented at the 20th IEEE Photovoltaic Specialists Conference in September 1988 in a technical paper entitled "Test and Evaluation of Vaccine Refrigeration Systems."

2.1.3 PV-Powered Water Pumping Systems

Goals:

Examine various system design strategies for PV-powered water pumping systems and identify configurations that optimize performance, economics and reliability.

Objectives:

1. Evaluate and quantify the side-by-side performance of three identical surface mounted centrifugal dc pump-motors, each coupled to PV arrays with the same maximum power rating, and operating under the following conditions: one pump-motor direct-coupled to a single-axis passive sun-tracking array, one pump-motor direct-coupled to a fixed array, and one pump-motor coupled through maximum power tracking electronics to a fixed array.

2. Analyze the performance of the three side-by-side systems in terms of optimal electrical and hydraulic system efficiencies for a variety of system head profiles and array configurations.

3. Measure the performance of the systems under actual operating conditions to verify analytical models that predict system performance for a diverse range of operating conditions and climates.

Accomplishments:

1. Pump-motor performance characterizations were completed for approximately ten commercially available products.

2. A directory of PV-powered water pumping systems component suppliers serving as a resource to the public, private industry and government agencies was developed.

3. A computer performance model and worksheets providing a sizing methodology for PV-powered water pumping systems was developed.

4. Results were presented at the 20th IEEE Photovoltaic Specialists Conference in September 1988 entitled "Analysis and Design Optimization of Photovoltaic Water Pumping Systems."

5. Evaluated the A.Y. McDonald Solar Sub, a centrifugal submersible pump operated by a brushless dc motor and the Grundfos ac submersible pump/motor operating from a power tracking inverter. Characterized the inverter and determine optimal array configurations. Three pump ends designed for different head profiles were tested.

2.1.4 Component Testing

Goals:

Determine charge controller reliability and provide useful information to the industry and system designers about charge controller and battery interactions in stand-alone PV systems.

Objectives:

1. Develop test procedures for charge controllers using simulated system components.

2. Evaluate charge controllers for stand-alone PV systems, and determine the effects of temperature, humidity and the number and frequency of cycles on performance of the charge controllers.

3. Evaluate charge controllers in both actual system configurations and in computer-controlled environmental chamber experiments.

Accomplishments:

1. The SE RES conducted initial characterization of eight commercially available charge controllers in actual systems.

2. Computer-controlled test facility was developed and used for charge controller evaluations,

which were completed at the end of 1989.

2.2 Design Assistance and Technology Transfer

2.2.1 Design Assistance

Goals:

Support the PV Design Assistance Center activities at SNLA in Latin America, the Caribbean and in the eastern U.S., and promote the effective implementation of PV technology.

Objectives:

1. Provide assistance for all phases of systems development including design and procurement specifications, system installations and system performance monitoring.

2. Promote effective and established system design guidelines, installation and operation techniques.

Accomplishments:

1. The SE RES developed design and procurement specifications and awarded the contract for the installation of six PV-powered vaccine refrigeration systems in Central America.

2. Electrical and mechanical designs were developed for Florida Power Corporation's 15 kW a-Si utility-interactive system in Orlando, Florida. Performance monitoring of the system continued with support from EPRI.

3. FSEC responded to over a hundred requests annually for PV systems design assistance and review. Many requests led to the implementation of PV systems for public and private entities.

2.2.2 Technology Transfer

Goals:

Effectively disseminate research results to the PV industry, government and end-users.

Objectives:

1. Share the experiences of SE RES with PV industry, electric utilities, designers and end-users to promote the effective development of stand-alone and utility-connected PV systems.

2. Develop technical reports, performance summaries, instructional materials and design notes to contribute to the research base and advancement of systems technology.

Status and Results:

1. Identified and addressed the concerns of the electric utilities in the implementation of photovoltaic technology.

2. Published over 50 technical papers in addition to a number of contract reports and other materials developed for SE RES and spin-off activities.

3. Participated in technical programs, conferences, and FSEC PV workshop activities.

4. Distributed over 1000 PV information packets at FSEC annually including many materials documenting the results of the SE RES program.

3. PROJECT OUTPUT

The following chronological listing gives a brief description of the significance and results of major programs for the SE RES. Other significant FSEC PV programs which are spin-offs or synergistic effects of the SE RES program are also listed with the associated sponsorship.

3.1 Major Program Accomplishments

1. **SE RES Prototype Systems (1983-89):** Three prototype grid-interactive residential PV systems and a flexible test facility were designed and constructed to evaluate different array mechanical designs, power conditioning equipment and PV array technologies in the hot, humid, salt-air Florida environment. Significant experience was gained in the areas of systems integration, electrical design and systems performance monitoring. Islanding tests were conducted in cooperation with the Georgia Power Company on several power conditioners to identify the potential for continued operation after loss of utility power. The building-block approach using stand-off array mounting proved more reliable and less costly than integral mount designs. Module electrical reliability was very high; minor problems were identified with module junction boxes.

2. **Tracking Array Field (1985-87):** Four computer-controlled tracking arrays were installed to investigate the energy enhancement for different tracking modes in the southeast climate. Converted to computer control in 1986, this method was found to be considerably more accurate than the initial active sun-sensing tracking control. Annual energy enhancements of 22-24 % for single-axis tracking and 40 % for two-axis tracking were measured at Cape Canaveral and validated with modelling.

3. **Central American Health Clinic Project (1986-87):** A cooperative effort between the U.S. DOE, SNLA, SE RES, OAS and PAHO, the goals of this project were to impact the reliability of health care through the implementation of large numbers of PV-powered vaccine

refrigeration systems in Central America. PV application workshops and health clinic site visits were conducted in Guatemala and Honduras in 1986. Design, performance and procurement specifications were developed that led to the solicitation of bids and contract award for the installation of six vaccine refrigeration systems in 1987: two each in Guatemala, Honduras and El Salvador.

4. **Vaccine Refrigeration Systems Testing (1987-1993):** Three PV-powered vaccine refrigerators were evaluated in a thermally controlled environment at the SE RES. The systems were tested for ability to maintain proper refrigerator/freezer temperatures over a range of ambient temperatures and ice making conditions. The energy consumption of the refrigerators was also measured for the same conditions. Finally, the PV system performance was also examined, particularly with regard to battery subsystem performance. Valuable information regarding the design and operation of the systems was gained. This research complemented the Central American Health Clinic project, and one of the refrigerator systems evaluated was installed for the six pilot systems in Central America.

5. **Water Pumping Systems Testing (1986-1990):** An experimental test facility was developed at the SE RES for the analysis and design optimization of PV-powered water pumping systems. Studies were conducted for centrifugal dc pump-motors coupled to fixed and tracking PV arrays and with a maximum power point tracker. Results showed these systems can be effectively optimized by properly designing the array configuration without the need for a maximum power point tracker. Tracking arrays were shown to enhance the hydraulic energy output above the insolation enhancement over fixed arrays.

6. **Thin-Film Module Evaluations (1987-1990):** A computer-controlled rapid-scan I-V curve tracer was developed to continuously measure and store the characteristics of a-Si PV modules. Valuable information on the long-term electrical performance and mechanical integrity of commercially available a-Si thin-film products was gained. Subsequent string-level tests have identified concerns in the application of a-Si thin-film modules to high-voltage utility-interactive systems. The results of the testing have made a positive impact on the development of thin-film products.

7. **Solar Progress (1987-current):** This project has been a cooperative effort between FPC, SE RES, UCF, SNLA and EPRI. The SE RES pre-qualified a-Si PV modules and developed the electrical and mechanical designs for Solar Progress, a 15 kWp a-Si utility-interactive system installed and operated by FPC. In operation since August 1988, the system provides essential information to the utilities and PV industry in the design and operation of a-Si thin-film utility-scale systems.

8. **Component Test Facility (1987-current):** A unique computer-controlled component test facility was developed to evaluate charge controllers for stand-alone applications. The system simulates PV array, battery and load, while using actual charge controllers. Stressing of the charge controllers through temperature and humidity cycling was conducted in environmental chambers. Initial characterization of the controllers in actual system configurations and environmental/cycle testing were completed at the end of 1989.

3.2 SE RES Spin-Off Programs

1. **U.S. Navy TACTS (1986):** Assistance was provided to the U.S. Navy in the design and evaluation of PV power systems for the Tactical Air Crew Training Systems (TACTS) located off the Carolina coast. Prototype TACTS systems were installed at FSEC to gain first hand operational experience. Post-installation field evaluations were made to verify design specifications and performance. The U.S. Navy and Air Force subsequently installed many TACTS type systems.

2. **Resource Assessment (1986-87):** As part of the SERI resource assessment program, spectral irradiance data was collected to validate models and to develop data sets for the performance characterization of new PV device materials. In addition, global and direct-normal insolation data were collected to validate the Perez anisotropic radiation model.

3. **PV Systems Design Assistance and Training Center (1986-1992):** This program sponsored by the Florida Energy Office gave the SE RES the vehicle to achieve a high level of technology transfer. PV workshops were held quarterly for system installers, utility representatives, engineers and architects. Emphasis was placed on established design practices and a working knowledge of PV system hardware through hands-on laboratory sessions. A course manual, laboratory manual and other instructional materials were developed to compliment the workshops. PV industry and product manufacturer directories were also compiled. Design assistance was routinely provided to potential PV system users.

4. **Florida Department of Transportation (1987-92):** A PV-powered lighting system for overhead highway guide signs was designed and installed with the cooperation of the Florida Department of Transportation (FDOT). The $25,000 system proved more economical than the $50,000 cost to extend utility service to the remote location. The system has operated reliably for over a year and data collection provided useful information and validation of design procedures. Follow-up programs with the FDOT identified other potential PV applications in the transportation sector and evaluate their feasibility, cost-effectiveness, transferability and impacts on transportation safety.

5. **PV Demonstration Projects (1987-1990):** Project administration, design and procurement assistance was provided by FSEC to support the Florida GEO in implementing pilot PV projects in Florida. The program successfully resulted in several cost-effective PV applications that have the potential for high visibility and transferability.

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