ABSTRACT

This document summarizes the detailed residential photovoltaic system designs developed by General Electric for Sandia National Laboratories. The specific designs are presented in SAND79-7056, SAND80-7148, SAND80-7170, SAND80-7171, SAND80-7172, and SAND80-7173.
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FOREWORD

The Detailed Residential Photovoltaic System Reference Designs Study was performed by the Advanced Energy Programs Department (AEPD) of the General Electric Company, Energy Systems and Technology Division under Sandia National Laboratories, Contract 13-8779. Mr. E.M. Mehalick served as the GE Program Manager, and Dr. G. Jones served as the Sandia Technical Monitor.

The project team led by AEPD included Massdesign Architects and Planners, Inc., who provided the details of the house design and analysis support related to the solar array installation and Johnson and Stover, Inc., who provided the installation drawings and specifications for the electrical equipment associated with the photovoltaic system.

The following individuals supported the program. From AEPD, Mr. G. O'Brien, Mr. R. Schaeffer and Mr. R. Felice provided electrical PV system design support; Mr. J. Parker and Mr. N. Truncellito provided system performance analysis; and Mr. R. Landes reviewed and selected system configurations. Mr. G. Tully, President of Massdesign supplied his direct support on all of the house designs and system integration. From Johnson and Stover, Mr. G. Johnson provided all of the electrical system design details. The program success was a direct result of the dedicated effort of all the team members.

The quality of the reports written during the program were enhanced by the review and suggestions of Dr. G. Jones at Sandia.
SECTION 1
INTRODUCTION

Objective

The objective of the Detailed Residential Photovoltaic (PV) System Reference Designs Program was to develop regionally appropriate detailed photovoltaic system designs covering the major system options for the 1986 time frame in habitable residences. The initial selection of the systems was based on previous work of all contractors in the PV residential area and consistent with the National PV Residential Program test plans. The designs were prepared for four regions of the country: the Southwest, the Northeast, the Southeast, and a temperate climate (e.g., California or Hawaii). A total of thirteen system configurations/regions were initially identified and six detailed designs developed. The systems considered various hardware options for the major subsystems. The output from the program included a separate report for each design with a complete system description, including design requirements, functional characteristics and site characteristics; a block diagram; full scale electrical line drawings; thermal drawings; pictorial layouts; a summary of performance characteristics and tradeoffs; and subsystem and component specifications. The reports have sufficient information to obtain detailed cost data from independent sources for installation of the proposed photovoltaic systems. The systems developed can be used as reference designs for typical equipment requirements, system performance estimates, installation details and system cost estimates.

The six designs completed are listed below:

1. A PV system for an all-electric Southwest residence employing a direct mount array
2. A PV/thermal side-by-side system for a Northeast residence
3. A PV system with battery storage for the Southwest employing a standoff array
4. A PV system for a passive house design for the Northeast
5. A PV system for a Southeast residence employing an integral mount array
6. A PV System for a temperate climate with either a standoff or an integral mounted array

The designs provided detailed drawings for installation of direct mounted modules (both shingle and batten types), standoff mounted modules and integral mounted modules.
This report provides a summary description of all the designs, a discussion of the initial system configuration review and selection, a summary of several design tradeoffs completed during the program and a discussion of design issues and concerns.

Background

A residential PV system consists of three primary subsystems: the array subsystem, the power processing and control subsystem and the storage subsystem. In the simplest configuration, the system is grid connected with feedback of excess energy to the utility and thus eliminating the storage subsystem (Figure 1-1). The economic viability of this system is dependent on the sellback credit ratio (a fraction of the normal utility charge to a customer) that the utility is willing to offer for the feedback energy. Previous studies have indicated that this system shows economic viability with a sellback credit of 50% or more in most regions of the country, References 1 and 2. The alternate basic configuration incorporates battery storage into the design (Figure 1-2). This option adds flexibility to the system and delivers more energy directly to the house loads; however, it is costly, adds control complexity and increases maintenance requirements.

In the broader sense, photovoltaic systems can also be combined with thermal systems; either in a side-by-side system configuration (Figure 1-3) or through the use of a combined PV/thermal collector. The side-by-side system uses separate

![Utility Feedback System](image)
PV and thermal arrays, both of which are currently available. Combined PV/T collectors were ultimately dropped from consideration because of poor observed and projected performance. All of the configurations include the power processing and control subsystem which is centered around the dc/ac inverter. This subsystem provides the interface between the dc photovoltaic array and the ac house loads and the utility.

Several alternate system configurations can also be considered for the side-by-side PV/thermal system (Figure 1-4). The first variation only provides supplemental thermal energy to the domestic hot water heater. This thermal system is less complex than the combined space heating and domestic hot water heating system and
shows better economic viability. The second variation considers the side-by-side PV/thermal system incorporated into a house utilizing fossil energy for space conditioning. The actual system design remains the same with economics slightly less attractive than for the all electric house, based on current costs of fossil fuels.

Another system configuration variation for any design includes a waste heat recovery unit for hot water heating. Several manufacturers are currently marketing these units which recover heat from the air conditioner or heat pump refrigerant as it leaves the compressor. The self-enclosed units consist of a heat exchanger, sealed motor pump, temperature sensor for the domestic hot water tank and a control valve to shut down the fluid flow when the hot water tank is at an upper temperature limit. The General Electric Hot Water Bank unit was used in one of the detailed designs. The annual results indicated a savings of 38% of the hot water requirements. Relatively low installation costs makes this unit an attractive option for the system.

The designs described in Section 3 address each of these basic and alternate system configurations.
SECTION 2
SYSTEM SELECTION

Residential PV system studies were reviewed to select configurations which appear most viable in 1986 in three specified geographic regions in the United States. The three regions were the Northeast, encompassing Madison, WI to Boston, MA; the Southeast covering Charleston, SC to Miami, FL; and the Southwest which includes the Albuquerque, NM and Phoenix, AZ climates.

Previous studies reviewed included the following:

- MIT/Lincoln Solar Research Facility Description
  - Arlington Solar Research Facility Description
  - Hybrid Systems Study
  - Optimization Hybrid Systems Study

- GE Space Division
  - Conceptual Design and Analysis Study
  - Regional Conceptual Design and Analysis Study
  - Photovoltaic Residential Prototype Definition Study

- Westinghouse
  - Conceptual Design and Analysis Study
  - Regional Conceptual Design and Analysis Study

- Aerospace Corporation
  - Photovoltaic Total Energy Residential Systems Study

- Spectrolab
  - Photovoltaic Systems Concept Study

- Martin Marietta
  - Photovoltaic Residential Prototype Definition Study

- MIT/Energy Laboratory
  - Grid-connected Photovoltaic Economic Study

Specific document numbers and dates of issue for each of the above indicated studies are contained in the list of references.
Classification and Evaluation of PV Systems

Classification of PV Systems

On the basis of collector configuration, each of the PV system concepts reviewed were classified into one of the following three categories:

- PV only
- Separate PV/Thermal
- Combined PV/Thermal

A basic schematic was prepared for each system along with a brief description of its configuration and operation. Table 2-1 lists all of the configurations. Evaluation of each system included a listing of major advantages and disadvantages, as well as a set of conclusions based on the results of regional performance and economic analyses conducted on previous studies. Details of this evaluation are presented in Appendix A.

Table 2-1. Summary of System Configurations

<table>
<thead>
<tr>
<th>Category</th>
<th>Identifier</th>
<th>System Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Only Systems</td>
<td>Ia</td>
<td>All Electric/Battery</td>
</tr>
<tr>
<td></td>
<td>Ib</td>
<td>All Electric/Feedback</td>
</tr>
<tr>
<td></td>
<td>Ic</td>
<td>Fossil Heating/Feedback</td>
</tr>
<tr>
<td></td>
<td>Id</td>
<td>All Electric/Maximum Power Tracking/Battery</td>
</tr>
<tr>
<td>Separate PV/Thermal Systems</td>
<td>IIa</td>
<td>All Electric/Solar Assisted Heat Pump/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIb</td>
<td>Direct Solar Heating/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIc</td>
<td>Solar Rankine Driven Heat Pump/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIId</td>
<td>Solar Absorption Cooling/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIe</td>
<td>Air Solar Boosted Heat Pump/Battery</td>
</tr>
<tr>
<td></td>
<td>IIf</td>
<td>Air Solar Assisted Heat Pump/Battery</td>
</tr>
<tr>
<td></td>
<td>IIg</td>
<td>Solar Boosted Heat Pump/Feedback</td>
</tr>
<tr>
<td>Combined PV/Thermal Systems</td>
<td>IIIa</td>
<td>Solar Assisted Heat Pump/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIIb</td>
<td>Direct Solar Heating/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIIc</td>
<td>Solar Boosted Heat Pump/Feedback</td>
</tr>
<tr>
<td></td>
<td>IIIId</td>
<td>Stand Alone/Direct Heating/Battery</td>
</tr>
</tbody>
</table>
The combination of generic system combinations is represented in the matrix shown in Table 2-2. The PV only system with feedback is the simplest system. The system complexity increases with the addition of battery storage or solar thermal options. Any of the blocks in the table represent a possible system configuration. Table 2-3 lists the subsystem options which can be included under each of the system configurations. Further options can exist within a subsystem as the type of array flat plate mounting technique. There are four possible mounting options: stand-off mounting, direct mounting, integral roof mounting or rack mounting. These various options were considered in final design selections.

Evaluation of PV Systems Within a Category

The following set of criteria was used to rate each system within each of the PV system categories:

- Economic/Performance Results
- Current Technology Status
- Projected Status for 1986
- Development Risk
- System Complexity
- Projected System Cost
- Regional Applicability
- Duplication of System Components

A rating designation of either good, fair or poor was then assigned to each system for each of the above criteria (see Appendix A). Based on these ratings, the systems were ranked within their category. The results of this ranking are presented below.

### PV ONLY SYSTEMS

<table>
<thead>
<tr>
<th>Rank</th>
<th>System Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ib, All Electric/Feedback</td>
</tr>
<tr>
<td>2</td>
<td>Ia, All Electric/Battery</td>
</tr>
<tr>
<td>3</td>
<td>Ic, Fossil Heating/Feedback</td>
</tr>
<tr>
<td>4</td>
<td>Id, All Electric/Maximum Power Tracking/Battery</td>
</tr>
</tbody>
</table>
Table 2-2. Generic System Configurations For Residential Demands

Table 2-3. Summary of Subsystem Options
Relative Effectiveness by Category (Collector) Type

Having ranked systems within a category, a comparative assessment was then made of the relative effectiveness of collector types as represented by the three categories. In this manner, similar systems appearing in more than one category (i.e., having different collector types) could be compared prior to making appropriate regional selections.

PV only solar arrays used in conjunction with an all electric load proved the most suitable system for residential use. Their potential economic viability was as good as, or better than, other solar energy options such as separate or combined PV/Thermal systems in all regions studied. Feedback generally proved the more cost effective approach when compared to battery storage for most systems investigated. Battery storage achieved cost effectiveness in high insolation areas, such as Phoenix.

It appeared that except at very low array costs, the higher thermal and electrical efficiencies of the separate PV/Thermal panel systems more than compensate for the potential savings in structural and installation costs provided by the combined PV/Thermal collectors. As a result, lower annual costs would be
possible with the separate PV/Thermal panel systems than with the combined collector systems. Separate PV/Thermal systems also exhibited some advantages in the Sunbelt areas, with the solar thermal systems capable of providing air conditioning, if appropriate solar cooling equipment is cost effective, or just domestic hot water.

Combined PV/Thermal systems, while they may have roof space savings and may have potential for lower cost in comparison to equivalent separate electrical and thermal collectors, have exhibited poor performance in recent tests. Therefore they currently do not offer significant promise.

The solar assisted heat pump (also referred to in the literature as a parallel HP system) proved more cost effective and less complicated than a solar boosted heat pump system (also referred to as a series HP system), with either the separate or combined PV/Thermal collector.

**System/Site Selections**

The goal of the program was to have a set of site/system selections which covered the major system options. Therefore, in addition to the results of the system rankings and relative evaluations, a qualitative analysis was also used to narrow the selected system configurations.

The array subsystem options were restricted to roof mounting due to the lack of ground area for the arrays in a residential development. Only flat plate modules were addressed. A roof-mounted concentrator was considered but eventually dropped with Sandia concurrence. The type of flat plate roof mounting was considered a key option since the different approaches required different installation details and, therefore, varying installation costs. Thus, direct-mounted, stand-off and integral array options received high consideration (See Figure 2-1) Rack-mounted arrays were not included due to limited applications. Rack-mounted residential arrays, however, were installed at the Southwest Residential Experiment Station. The reader is directed to that program for details of this mounting approach.

Similarly, the differences between feedback and battery systems received high consideration and a separate design was developed for each. However, the differences in installation details between a stand-alone system and a grid-connected battery system were considered insignificant and separate designs were not developed. PV-only systems with feedback were used in most of the remaining
designs since the systems have shown the highest potential in most previous studies.

For PV/Thermal systems, side-by-side collectors were considered. A hot water only system was addressed as an option of the solar assisted heat pump system configuration. Solar cooling was eventually ruled out since solar thermal cooling systems are not currently economically viable. Similarly, combined PV/Thermal collectors were eliminated due to their current low performance and limited region applicability.

For the power conditioning subsystem, installation details do not vary significantly for the different types of units available. Two primary options were considered in the designs based on currently available hardware.

Finally, in addition to the three geographic regions initially considered, a temperate climate with low space conditioning loads rounded out the weather environment. House design variations appropriate for each of the environments also were developed.

Summarizing all the considerations described, the six systems and regions identified in Table 2-4 were selected. Subsystem options for several of the designs were added to further expand the total coverage of hardware variations. Table 2-5 lists these options.

![RACK](image)
![STANDOFF](image)
![DIRECT](image)
![INTEGRAL](image)

**Figure 2-1. Alternate Mounting Techniques for PV Modules**
### Table 2-4. Selected System Designs

<table>
<thead>
<tr>
<th>System Configuration</th>
<th>Mounting Configuration</th>
<th>Location</th>
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<tbody>
<tr>
<td>PV-only with feedback</td>
<td>Direct</td>
<td>Southwest</td>
</tr>
<tr>
<td>PV-only with battery storage</td>
<td>Standoff</td>
<td>Southwest</td>
</tr>
<tr>
<td>PV-only for a passive house design</td>
<td>Direct</td>
<td>Northeast</td>
</tr>
<tr>
<td>PV-only with feedback</td>
<td>Integral</td>
<td>Southeast</td>
</tr>
<tr>
<td>PV-only with feedback</td>
<td>Integral and Standoff</td>
<td>Temperate Climate</td>
</tr>
</tbody>
</table>

### Table 2-5. Summary of Subsystem Options Addressed in the Designs

<table>
<thead>
<tr>
<th>ARRAY SUBSYSTEM</th>
<th>DESIGN NUMBER</th>
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</thead>
<tbody>
<tr>
<td>- GE PV Shingle Direct Mount Module</td>
<td>1 and 4</td>
</tr>
<tr>
<td>(Two Design Generations)</td>
<td></td>
</tr>
<tr>
<td>- ARCO Solar Batten Direct Mount Module</td>
<td>2</td>
</tr>
<tr>
<td>- Solarex Stand-Off Mounted Frame Module</td>
<td>3</td>
</tr>
<tr>
<td>- Side-by-Side Flat Plate Thermal Collectors</td>
<td>2</td>
</tr>
<tr>
<td>- Integral Glass Laminated Modules</td>
<td>5 and 6</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>STORAGE SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>- Feedback Energy to Utility</td>
<td>1, 2, 4, 5 and 6</td>
</tr>
<tr>
<td>- Lead Acid Battery Storage</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>HVAC SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>- Heat Pump (HP)</td>
<td>1, 2, 3, 4, 5</td>
</tr>
<tr>
<td>- Fossil Heating/Vapor Compression Cooling</td>
<td>2</td>
</tr>
<tr>
<td>- Solar Assisted HP</td>
<td>2</td>
</tr>
<tr>
<td>- Solar Domestic Hot Water (DHW)</td>
<td>2</td>
</tr>
<tr>
<td>- Space Conditioning Heat Recovery for DHW</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>POWER PROCESSING AND CONTROL SUBSYSTEM</td>
<td></td>
</tr>
<tr>
<td>- Windworks Gemini Inverter</td>
<td>1, 3 and 4</td>
</tr>
<tr>
<td>- Abacus Sunverter</td>
<td>2, 5 and 6</td>
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</tbody>
</table>
A new house design was developed for each application. The designs were all single family detached houses but they included one-story, two-story and zero-lot-line type configurations. The floor areas ranged from 142 m² to 161 m² with south facing roof areas ranging from 44 m² to 104 m². All the houses were assumed newly constructed in 1986. The designs included basic energy conservation features and additional passive design features projected for 1986 but consistent with the aesthetic design of the house.

The electrical energy derived from the PV system serves the normal household electrical requirements including general appliances, lighting, cooking and hot water heating. In general, the homeowner was considered the system user; therefore, operation and maintenance requirements typical of conventional HVAC systems were assumed. The systems excluded instrumentation, since a mature system installation was assumed. Specifications for equipment were based on currently available components or similar currently available equipment if the component was not available.

To evaluate the performance of the system designs, typical hourly electrical load profiles and space conditioning demands for the house were used. These load profiles were developed in the GE Regional Residential Study, Reference 5, and updated in the Residential Load Center Program, Reference 14. All the system performance analyses were completed based on these hourly loads and using Typical Meteorological Year (TMY) weather data as developed by Sandia National Laboratories. Life cycle cost analyses, based on system performance results and system cost estimates, were used for system sizing and tradeoffs.

The six designs developed included:

1. A PV system for an all-electric Southwest residence employing a direct mount array
2. A PV/thermal side-by-side system for a Northeast residence
3. A PV system with battery storage for the Southwest employing a standoff array
4. A PV system for a passive house design for the Northeast
5. A PV system for a Southeast residence employing an integral mount array
6. A PV System for a temperate climate with either a standoff or an integral mounted array
A separate report was written for each design, References 3 through 8. A complete set of full sized drawings were also delivered to Sandia for each of the designs. The system sizes ranged from 4 kW to 8 kW systems. The system sizing for all the designs was completed on a marginal cost basis. A consistent set of economic assumptions was used and they are summarized in Table 3-1.

All of the economic calculations were completed for a 1986 start in constant 1980$. The overall average inflation rate of 5 percent was assumed through the time frame of the analysis. This value is low according to current rates but since the marginal cost analysis becomes independent of the inflation rate and to maintain similarity to previous work, this value was used. In addition, a resultant homeowner mortgage rate of 10 percent for a 20-year loan was assumed with a marginal income tax rate of 35 percent for the homeowner. This is equivalent to a taxable income of approximately $25,000 at present tax rates. Since several states and local communities have already exempted solar systems from property tax, no additional property tax were assumed. These figures imply an annual cost or "fixed charge" of about 9.1% of the initial photovoltaic system cost. Annual operating costs were assumed to be $100/year for operation and maintenance and 0.5% of system cost for insurance. All components of the solar system were assumed to have the same lifetime as the system (20 years) except for batteries (10 years).

An electricity price escalation of 4% over inflation was also used in the analysis, although the marginal benefit/cost analysis allows the extension to other escalation rates and system lifetime assumptions by a constant adjustment factor as done in Reference 16.

<table>
<thead>
<tr>
<th>Table 3-1. Economic Assumptions for Optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 1986</td>
</tr>
<tr>
<td>• General Inflation Rate: 5%</td>
</tr>
<tr>
<td>• Insurance: 0.5% of Capital Cost</td>
</tr>
<tr>
<td>• Electricity Price Escalation: 4% Over Inflation</td>
</tr>
<tr>
<td>• Mortgage Rate: 10%</td>
</tr>
<tr>
<td>• Tax Bracket: 35%</td>
</tr>
<tr>
<td>• No Property Tax</td>
</tr>
<tr>
<td>• System Life: 20 years</td>
</tr>
<tr>
<td>• Maintenance: $100/Year</td>
</tr>
<tr>
<td>• 1980$</td>
</tr>
<tr>
<td>• Battery Life: 10 Years</td>
</tr>
</tbody>
</table>
Cost estimates were made for each of the systems to calculate the levelized annual costs. The array cost assumed was the National PV Program goal of 70¢/peak Watt or $700/kWp factory price. Including the markups, the cost is $925/kWp on site. The balance of system costs were made up of array installation estimates, power conditioning subsystem costs, storage subsystem costs and remaining equipment costs. Power conditioning costs were based on 1986 price projections. The 1986 battery costs were varied from $0/kWh to $150/kWh to assess the effect of these values on system sizing. All the costs are in 1980$ and include in general, two 15% markups for distribution and contractors. These markups are probably low, but were used in the analysis until more detailed numbers are available for distribution networks.

Regional energy price estimates were assumed for each design to determine the system-levelized annual benefits.

The following subsections provide a brief summary description of each of the designs.
A PV SYSTEM FOR AN ALL-ELECTRIC RESIDENCE IN THE SOUTHWEST

A simple, utility feedback, photovoltaic system was designed for a single story all electric house in the Southwest. The two major system elements are the photovoltaic array and the power conversion subsystem. The photovoltaic array uses the GE Block IV shingle module in a direct mount configuration. The system was sized nominally at 8 kWp based on minimum life cycle costs but key parameters were evaluated parametrically and changes in some of the assumptions were also evaluated. For example, sellback rates were varied parametrically indicating at higher sellback rates (greater than 50%) all of the available roof area should be utilized for the array, resulting in the 8 kW sized system. As the sellback rates decreased to 30% or less, a 5 kW system size becomes more appropriate. Assumptions of fixed and variable system capital costs also affect system sizing, implying smaller system sizes as fixed costs are lowered.

The system design is applicable to all regions. The effects of varying electrical load level on the system economics resulted in cost-to-benefit ratio insensitivity to load level at sellback rates above 50%. Therefore, system size would not be affected by slight variations in load levels. Profile changes and dramatic changes in the load would affect system sizing.
HOUSE DESCRIPTION

- The house design is for a SINGLE- STORY residence of NEW CONSTRUCTION for the Southwest region of the country.

- The design includes PASSIVE SOLAR FEATURES and ENERGY CONSERVATION FEATURES projected for 1986.

- There is 149 m² (1600 ft²) living area with 104 m² (1120 ft²) south facing roof area.

- The house is ALL ELECTRIC with a 3-ton heat pump and electric hot water heater.

- The site layout has a detached garage with a lot area between 1/6 and 1/4 acre.
SYSTEM DESCRIPTION

- The system is grid connected with an 8 kW NOCT array rating using a GE BLOCK IV SHINGLE MODULE ARRAY. The array consists of a total of 475 MODULES COVERING 93 m² in a redundant parallel-series network.

- The power conversion subsystem uses a 10 kVA LINE COMMUTATED MAX POWER TRACKING INVERTER to convert dc generated power to ac. A 15 kVA SINGLE PHASE ISOLATION TRANSFORMER is used to match ac supply voltage to the load.

- The system operation is PARALLEL AND SYNCHRONIZED WITH THE UTILITY.

- Excess generated power is FEEDBACK to the utility.

- The system represents the SIMPLIEST PHOTOVOLTAIC DESIGN with a minimum of components and controls.

---

PV ARRAY

DC/AC INVERTER

MAX POWER TRACK

GENERAL LOADS

HEAT PUMP

HOT WATER

- ROOF MOUNTED SHINGLE

93 m²
SYSTEM OPERATION

- The system has automatic startup and shutdown control.
- The system automatically shuts down with loss of the utility.
- System operation is summarized by the sequence below.

1. At sunrise in the automatic "on" mode, the ac and dc contactors will close when the array bus voltage reaches a threshold of 180 Vdc.
2. During the daylight period the inverter will continue to operate as long as there is a net power output.
3. The inverter will track the maximum power operating point within ±1 percent over the range of 180 to 220 Vdc.
4. The interruption of utility-supplied power will cause the dc contactor to open and remain open until line voltage is restored.
5. At sunset, the inverter ac and dc contactors will open when the net power output falls to zero. These contactors will remain open throughout the night to eliminate the majority of the inverter parasitic losses.

![Utility Service Diagram](image-url)
PHOTOVOLTAIC ARRAY

- The array consists of shingle PV modules connected in a 25 series by 19 parallel network covering 93 m² of roof area.

- The array is oriented due south with a roof pitch of 26°. The overall cell packing efficiency is 76.3% over the 93 m².

- The modules are direct mounted on top of the roofing felt and plywood roof sheathing. They form a weather tight roof.

- The modules are installed by an overlapping procedure similar to conventional shingles. Four electrical interconnections are made with flathead machine screws per module and two roofing nails are used per module for attachment to the roof.
PHOTOVOLTAIC MODULES

- The module was developed by General Electric Company as part of the JPL Block IV procurement.

- The module uses 19 ARCO-SOLAR 100 mm cells with an unencapsulated efficiency of 12.3% connected in a series circuit.

- For a NOCT of 64°C, the maximum power output is 17.14 Watts and 7.3 Volts at SOC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).

- A summary of module characteristics include:
  - Module weight: 3.85 kg
  - Total cell area: 0.1492 m²
  - Exposed module area: 0.1955 m²
  - Module packing factor: 0.763
POWER CONVERSION SUBSYSTEM

- The PCS provides the interface between the PV array and the normal residential utility service and loads.
- The subsystem consists of three main components: the inverter, the dc filter and transformer along with the associated control circuitry.
- The subsystem is sized for 10 kW of power output with a 15 kVA transformer sized to accommodate the out of phase ac voltage (VARS) and current.
- The subsystem can be obtained from the Gemini Corporation, marketed by Windworks, Inc.

KEY INVERTER DESIGN CHARACTERISTICS

- OUTPUT POWER RATING: 10 kW continuous
- OUTPUT VOLTAGE: 240 VAC Utility Residential Service
- INPUT VOLTAGE: 200 + 20 Vdc
- FULL LOAD POWER FACTOR: 60% Minimum
- FULL LOAD EFFICIENCY: 92% Minimum
- FULL LOAD HARMONIC DISTORTION: 30% Maximum
- OPERATING TEMPERATURE: 0°C to 40°C
PV INTERFACE WITH UTILITY AND HOUSE SERVICE

- Interface arrangements employ CONVENTIONAL WIRING RUNS AND EQUIPMENT as much as possible to facilitate acceptance by local regulatory authorities.

- The PV array source is treated as a CONVENTIONAL UTILITY SERVICE entrance to the residence with the raceway parallel to utility line.

- An external disconnect switch provides an external break. By strict code interpretation, this switch may be eliminated, especially as PV installations increase.

- An equipment room of 6.1 m² floor area is located on the west end of the house. The equipment room will also house the heat pump and electric hot water heater and can be used for extra storage.

- All PV related equipment is wall mounted, except for the transformer.
ARRAY SIZING

- Energy sellback price the utility is willing to pay the homeowner affects system sizing.
- Sellback rates greater than 50% imply full roof arrays (93 m²).
- Lower sellback rates (~30%) imply roof arrays of 50 m².
- At higher sellback rates, the economics are insensitive to load level.

**ALBUQUERQUE**

**PHOENIX**

---

**PHOENIX**

Array Area = 92.9 m²
DESIGN PERFORMANCE

- Net system output for both Albuquerque and Phoenix is greater than the total electrical load.
- Phoenix shows better load matching characteristics.
- Overall system efficiency based on incident insolation for gross array area is within the 8% to 8.4% range for the Southwest.

![Graphs showing energy output and load for Phoenix and Albuquerque.](image-url)
A side-by-side photovoltaic/thermal system with utility feedback was designed for a two-story all-electric house in the Northeast. The three major system elements are the photovoltaic array, the electric power conversion subsystem, and the thermal subsystem. A key to the sizing of the PV and thermal array is the relative cost of each system. Therefore, the ratio of the costs associated with each system was varied parametrically to define ultimate sizing of the PV and thermal array. In general, the results indicate larger PV array area and minimal thermal array area for the set of cost assumptions. A thermal system of adequate size, however, was selected to assure sufficient design details for determining system installation costs. The PV system was sized nominally at 6.7 kWp based on roof area limitations, side-by-side with a 19.5 m$^2$ flat plate thermal collector array. The 73.6 m$^2$ photovoltaic solar array uses a batten type solar cell module, being developed by ARCO-Solar as part of the JPL block IV procurement, and the 19.5 m$^2$ thermal array uses a Sunworks Solector$^\text{TM}$ collector which is representative of available thermal collectors.

A separate thermal system design was also developed for a side-by-side solar hot water system for comparison. A solar hot water system, since it was less complex and has less components, showed better economic viability than the parallel solar heat pump space heating and hot water system. Both systems probably will be available in the 1986 time frame.
HOUSE DESCRIPTION

- The house design is for a TWO-STORY residence of NEW CONSTRUCTION for the Northeast region of the country.

- The design includes PASSIVE SOLAR FEATURES and ENERGY CONSERVATION FEATURES projected for 1986. A GREENHOUSE is attached on the southern exposure.

- There is 158 m² (1700 ft²) of living area with 101 m² (1090 ft²) south facing roof area.

- The house is ALL ELECTRIC with a 3-ton heat pump and electric hot water heater.

- The site layout has a two car attached garage with a lot area of approximately 1/4 acre.
SYSTEM DESCRIPTION

- The system consists of a separate GRID CONNECTED photovoltaic array with a 6.7 kW NOCT rating and a thermal array which provides a SOLAR ASSIST to the HEAT PUMP and DOMESTIC HOT WATER HEATER.

- The PV array uses the ARCO SOLAR BLOCK IV BATTEN SEAM MODULE in a 28 series by a 4 parallel circuit arrangement covering 73.6 m² of roof area.

- The thermal array uses 10 Sunworks Solector® collectors covering 19.5 m² of roof area.

- The power conversion subsystem uses a 8 kW SELF-COMMUTATED MAX POWER TRACK-ABACUS INVERTER to convert dc generated power to ac and to match ac supply voltage to the load.

- The system operation is PARALLEL AND SYNCHRONIZED WITH THE UTILITY.

- Excess generated power is FEDBACK to the utility.

- The thermal subsystem has a 350 GALLON WATER THERMAL STORAGE component and an 80 GALLON DOMESTIC HOT WATER TANK.
PV SYSTEM OPERATION

- The system has AUTOMATIC STARTUP and SHUTDOWN control.
- SYSTEM OPERATION is summarized by the sequence below.

1. At sunrise in the automatic "on" mode, the ac line contactor is closed and the phase lock loop and maximum power tracker are energized.

2. During the daylight period, the inverter will continue to operate until the dc input voltage falls below 160 V.

3. The inverter will track maximum power point within ±1 percent over the range of 160 to 240 Vdc.

4. The interruption of utility-supplied power will cause the ac contactor to open and remain open until line voltage is restored.

5. At sunset, the inverter ac contactor will open when the net power output falls to zero. This contactor will remain open throughout the night to eliminate any parasitic losses.
THERMAL SUBSYSTEM

- The system has AUTOMATIC STARTUP AND SHUTDOWN control.

- A control center regulates operational sequences for solar thermal energy collection, storage and utilization loops, as well as auxiliary backup.

- SYSTEM OPERATION is summarized by the sequence below:

1. The collector and storage loop pumps are activated when a temperature difference of 8.3°C is registered between the collector surface and the bottom of the thermal energy storage (TES) tank.

2. Operation continues until the temperature difference is less than 2.8°C.

3. Flow is diverted through the heat pump when the TES temperature is greater than 87.8°C.

4. Circulation is activated from the TES to the domestic hot water (DHW) tank when a temperature difference of 3.3°C exists between the top of the TES tank and the bottom of the DHW tank and continues until the temperature difference falls to less than 1.1°C.

5. Flow is activated to the hydronic coil when the TES temperature is 26.7°C or greater. This is an adjustable setting.

6. If the hydronic coil cannot meet the space demand, then the flow to the hydronic coil is stopped and the heat pump activated and operated in a conventional mode.
PHOTOVOLTAIC ARRAY

- The array consists of batten PV modules connected in a 28 series by 4 parallel network covering 73.6 m² of roof area.
- The array is oriented due south with a roof pitch of 40°.
- The modules are direct mounted on top of the roofing felt and plywood roof sheathing. They form a weather tight seal.
- The modules are installed by an overlapping procedure similar to a conventional batten seam roof. The modules are held in place by clips screwed into the roof. Electrical interconnections are made with patented connectors which run along the batten seam.
PHOTOVOLTAIC MODULES

- The module was developed by ARCO Solar, Inc. of Chatsworth, California, as part of the JPL Block IV procurement. The development module currently uses circular cells.

- The module specified for the design is a high density version which uses ARCO-Solar 70 mm square cells with 16 cells connected in series and 7 parallel circuits for a total of 112 cells per module.

- For a NOCT of 63°C, the maximum power output is 60.0 Watts, and 6.0 Volts at SCC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).

- A summary of module characteristics include:
  - Module weight: 4.8 kg
  - Total cell area: 0.5488 m²
  - Exposed module area: 0.657 m²
  - Module packing factor: 0.835
  - Nominal size: 1.2 m long by 0.58 m wide
THERMAL COLLECTORS

- The thermal collector is a flat plate model called the Solector and it is currently available from Sunworks of New Haven, Connecticut.
- The collector uses a SELECTIVELY COATED COPPER absorber, with a SINGLE-GLAZING of low iron, 1/4 inch tempered glass in an extruded ALUMINUM frame.
- The collector has INTEGRAL MANIFOLDING for ease of installation.
- The design installation consists of 10 collectors covering 19.5 m².
- A summary of collector characteristics include:
  - Collector size: 213 m long by 0.91 m wide
  - Collector weight: 51.4 kg
  - Effective absorber area per panel: 1.7 m²

Data from Sunworks Brochure
POWER CONVERSION SUBSYSTEM

- The Power Conversion Subsystem (PCS) provides the interface between the PV array and the normal residential utility service and loads.

- The subsystem consists of three main components: the inverter, the dc filter and the transformer along with the associated control circuitry, packaged in a single unit.

- The unit is manufactured by Abacus Controls, Inc., Sommerville, New Jersey.

- The subsystem is sized for a 8 kW POWER OUTPUT with the transformer sized to accommodate the adjustment of the ac voltage and current.

- Characteristics are summarized below.

KEY INVERTER DESIGN CHARACTERISTICS

OUTPUT POWER RATING: 8 kW CONTINUOUS
OUTPUT VOLTAGE: 240 Vac Utility Residential Service
INPUT VOLTAGE: 200 ± 40 Vdc
FULL LOAD POWER FACTOR: Unity
FULL LOAD EFFICIENCY: 90% Minimum (over 25% to 88% of operating range)
FULL LOAD HARMONIC DISTORTION: 5% Maximum
PV INTERFACE WITH UTILITY AND HOUSE SERVICE

- Interface arrangements employ CONVENTIONAL WIRING RUNS AND EQUIPMENT as much as possible to facilitate acceptance by local regulatory authorities.

- The PV array output is treated as a CONVENTIONAL UTILITY SERVICE ENTRANCE to the residence with the raceway parallel to utility line.

- An external disconnect switch provides a means to externally disconnect the array and the power conversion unit. By strict code interpretation, this switch may be eliminated, especially as PV installations increase.

- An equipment room of 8.2 m² floor area is located on the west end of the house. The equipment room also houses the heat pump, electric hot water heater and thermal storage tank and can be used for extra storage.

- The Power Conversion Unit is floor-mounted, and all of the remaining PV-related equipment is wall-mounted.
ARRAY SIZING

- Energy sellback price the utility is willing to pay the homeowner and relative PV system cost to thermal system cost affects the overall system sizing.
- Sellback rates greater than 50% imply full roof arrays.
- Marginal costs were used in the system sizing.
- For thermal system costs greater than PV system costs, system sizing results in more PV array area and less thermal collector area.
- Thermal collector area was sized primarily to provide a thermal system of adequate size for cost estimates.

![Graphs comparing PV array area to thermal collector area for Boston and Madison](image)

### Equations

- **Boston**
  - \( P_G / P_E \) = 0.5
  - \( C_T / C_{PV} = 3 \)
  - \( C_T / C_{PV} = 2 \)
  - \( C_T / C_{PV} = 1 \)
  - \( C_T / C_{PV} = 1/2 \)

- **Madison**
  - \( C_T / C_{PV} = 1.7 \)

### PV System Cost
- \( F_{PV} \cdot C_{PV} \times \text{Area}_{PV} \)

### Thermal System Cost
- \( F_T \cdot C_T \times \text{Area}_T \)

### Energy Equations
- \( E = P_G \cdot t \)
- \( P_E = E / t \)
DESIGN ELECTRICAL PERFORMANCE

- Net PV system output for both Boston and Madison is approximately 67% of the load requirements.
- Approximately 39% of the PV output is utilized directly in the house and the remainder fed back to the utility.
- The net electrical system output in the summer months is greater than the load requirements, mainly due to the thermal system providing the hot water requirements.
- Overall PV system efficiency based on incident insolation for gross array area is approximately 8.5% for this design in the Northeast.

### BOSTON

- **Load**: 12.7 MWh
- **PV System Output**: 8.6 MWh
- **Utility Make-Up**: 5.2 MWh
- **Sell Back**: 3.5 MWh

### MADISON

- **Load**: 14.2 MWh
- **PV System Output**: 10.2 MWh
- **Utility Make-Up**: 5.3 MWh
- **Sell Back**: 3.5 MWh
DESIGN THERMAL PERFORMANCE

- Net thermal system output ranges from 35 to 39% of the load requirements.
- Approximately 24% of the space heating requirements and 66% of the DHW requirements are supplied by the solar thermal system.
- All of the thermal requirements are met in the summer months.
- Overall thermal system efficiency is approximately 22% for this design in the Northeast.

![Graphs showing monthly energy consumption for space heating and domestic hot water for Boston and Madison.](image)
A photovoltaic system with on-site storage was designed for a single story all electric house in the Southwest. The three major system elements are the photovoltaic array, the battery storage subsystem, and the power conversion subsystem. Marginal life cycle cost analysis was used for system sizing of the array and battery. The analysis considered various combinations of array and battery sizes and provided parametric performance results. In general, the results indicate a relatively small battery capacity for each array size considered, based on current cost estimates.

The nominal size array output is 6.07 kWp. The modules are standoff mounted. The baseline design battery capacity for Phoenix is 20 kWh. An Albuquerque application, where increased electricity cost and improved load match exist, requires a larger capacity of 25 kWh. Reduced battery capital costs indicate an increased optimum capacity for all of the array sizes considered. The array size and associated array performance ultimately bound the battery capacity, if cost constraints are neglected. The system economics also indicate a sensitivity to total electrical load requirements for all battery costs considered. Therefore, changes in the load requirements and profile affect system sizing and particularly the optimum battery capacity.
HOUSE DESCRIPTION

- The house design is for a SINGLE-STORY residence of NEW CONSTRUCTION for the Southwest region of the country.
- The design includes PASSIVE SOLAR FEATURES and ENERGY CONSERVATION FEATURES projected for 1986.
- There is 149 m² (1600 ft²) living area with 104 m² (1120 ft²) south facing roof area.
- The house is ALL ELECTRIC with a 3-ton heat pump and electric hot water heater.
- The site layout has a detached garage with a lot area between 1/6 and 1/4 acre.
SYSTEM DESCRIPTION

- The system is grid connected with a 6.07 kW array rating using a SOLAREX BLOCK IV INTERMEDIATE LOAD MODULE ARRAY. The array consists of a total of 100 MODULES with 76.2 m² of aperture area in a parallel-series network.

- The battery storage subsystem includes a 20 kWh LEAD ACID BATTERY to store PV generated power. A BATTERY CHARGE CONTROLLER controls the bus voltage. A larger capacity of 25 kWh is required for an Albuquerque location.

- The power conversion subsystem (PCS) employs a 6 kVA LINE COMMUTATED INVERTER to convert PV generated power to ac. A 10 kVA SINGLE PHASE ISOLATION TRANSFORMER matches ac supply voltage to the load.

- The system operation is PARALLEL AND SYNCHRONIZED WITH THE UTILITY, without feedback.

- Excess generated power is SHUNTED to ground. Heating domestic hot water with the excess energy is a design option.
SYSTEM OPERATION

• The system has automatic startup and shutdown control.

• The system automatically shuts down with loss of utility power.

• System operation is summarized by the sequence below.

1. At sunrise, in the automatic "on" mode, the ac and dc contactors will close when the array bus voltage reaches a threshold of 120 Vdc.

2. During daylight hours the PV array/battery system will supply the load demand. Excess power is applied to the charge battery.

3. When the battery is fully charged (156 Vdc), the battery charge control sheds PV branch circuit(s) which reduces current flow. Should the voltage fall below 144 Vdc, the charge control adds circuit(s).

4. The battery delivers load demands when the voltage level is greater than 120 Vdc and the solar array output is not adequate to meet these demands.

5. The battery supplies power until the bus voltage falls below 120 Vdc; at this point the ac and dc contactors will open.

6. If the battery is depleted, a 128-minute time lag is imposed before another discharge attempt is made, thus precluding deep discharges.

7. Twice a month, during off-peak hours, the PCS initiates battery equalization to 173 Vdc.
PHOTOVOLTAIC ARRAY

- The array consists of STAND-OFF PV modules connected in a 10 SERIES by 10 PARALLEL NETWORK with 76.2 m² of aperture area.
- The array orientation is due south with a ROOF PITCH OF 26°. The overall module packing efficiency is 85.3% over the 76.2 m².
- The modules are mounted on WOOD 2 x 4 inch STAND-OFFS. Conventional asphalt shingles beneath the modules provide a weathertight roof.
- The module frame fits into aluminum clips mounted to the stand-offs and attaches to the clips by four sheet metal screws. Electrical interconnection between modules is made with AMP Inc. connectors and standard cables.
PHOTOVOLTAIC MODULES

- The module is manufactured by SOLAREX CORP., of ROCKVILLE, MARYLAND, and was developed as part of the JPL Block IV procurement.

- The module uses Solarex 95 mm SQUARE CELLS with 36 cells connected in series and 2 parallel circuits for a total of 72 cells per module.

- For an estimated stand-off NOCT of 60°C, the MAXIMUM POWER OUTPUT is 60.7 Watts, and 13.9 Volts at SOC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).

- A summary of module characteristics include:
  - Module weight: 15.9 kg
  - Total cell area: 0.650 m²
  - Exposed module area: 0.762 m²
  - Module packing factor: 0.853
  - Nominal size: 1.2 m long by 0.64 m wide
The Power Conversion Subsystem (PCS) provides the interface between the PV array/battery and the normal residential utility service and loads.

The subsystem consists of three main components: the INVERTER, the DC FILTER and TRANSFORMER along with the associated control circuitry.

The subsystem rating is 6 kVA of power output with a 10 kVA transformer sized to accommodate the out-of-phase ac voltage and current.

The subsystem characteristics are summarized in the table below.

The GEMINI CORPORATION, of MUKWONAGO, WISCONSIN, manufactures the subsystem components and WINDWORKS, INC. markets them.

**KEY INVERTER DESIGN CHARACTERISTICS**

<table>
<thead>
<tr>
<th>OUTPUT POWER RATING</th>
<th>10 kVA CONTINUOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT VOLTAGE:</td>
<td>240 VAC Utility Residential Service</td>
</tr>
<tr>
<td>INPUT VOLTAGE:</td>
<td>138 ± 18 Vdc</td>
</tr>
<tr>
<td>FULL LOAD POWER FACTOR:</td>
<td>60% Minimum,</td>
</tr>
<tr>
<td>FULL LOAD EFFICIENCY:</td>
<td>92% Minimum</td>
</tr>
<tr>
<td>FULL LOAD HARMONIC DISTORTION</td>
<td>30% Maximum</td>
</tr>
<tr>
<td>OPERATING TEMPERATURE:</td>
<td>0° to 40°C</td>
</tr>
</tbody>
</table>

![Diagram of Power Conversion Subsystem]
The battery storage subsystem provides the energy storage capacity for the solar generated power.

The subsystem consists of two main components: the BATTERY and the CHARGE CONTROLLER.

The subsystem includes a 20 kWh LEAD-ACID battery made up of 64 series-connected cells producing a nominal 135 Vdc output.

The charge controller maintains the voltage within a 144 to 156 Vdc range which is indicative of full battery charge.

ESB INCORPORATED, EXIDE POWER SYSTEMS DIVISION, of YARDLEY, PENNSYLVANIA, manufactures the battery. GENERAL ELECTRIC COMPANY manufactures the charge controller.
ARRAY/BATTERY SIZING

- The array/battery sizing uses MARGINAL COSTS and BENEFITS.
- Battery capital cost affects the relative size of the array and battery.
  - Battery capital costs greater than $100/kWh imply smaller batteries (~20 kWh).
  - Lower battery capital costs imply larger capacities for fixed array sizes.
- System economics are sensitive to load level for all battery costs. New optimum system sizes must be developed for significantly varying load levels.

PHOENIX

CELL AREA = 65.0 m²

<table>
<thead>
<tr>
<th>BATTERY COST ($/kWh)</th>
<th>LIFE CYCLE RATIO (LCCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

BATTERY CAP. = 20 kWh

ALBUQUERQUE

CELL AREA = 65m²

<table>
<thead>
<tr>
<th>BATTERY COST ($/kWh)</th>
<th>LIFE CYCLE RATIO (LCCR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>1.5</td>
</tr>
<tr>
<td>100</td>
<td>1.0</td>
</tr>
<tr>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

BATTERY CAPACITY = 20kWh
DESIGN PERFORMANCE

- Total net system output for both Phoenix and Albuquerque is approximately 69% of the load requirements.
- Phoenix shows better load matching characteristics.
- Overall system efficiency based on incident insolation for gross array area is within the 5.9 to 6.1% range for the Southwest.
PASSIVE HOUSE DESIGN FOR THE NORTHEAST

A 4.1 kW grid-connected PV system with utility feedback is designed for a passively heated house having low total electrical load requirements. The major system elements are the photovoltaic array and the power conversion subsystem. Marginal life cycle cost analysis was used for system sizing. The analysis considers various array sizes and provides parametric performance results. In general, with utility sellback rates of 50% or greater, the results indicate a PV array size as large as the available roof area. This design considers a low energy consuming house with a minimum of available roof area. The 50 m² solar array uses a rectangular shingle solar cell module being developed by General Electric. The array is wired in a redundant series/parallel matrix.
The house design is a TWO-STORY residence with a basement of NEW CONSTRUCTION for the Northeast region of the country.

The design includes PASSIVE SOLAR FEATURES and ENERGY CONSERVATION FEATURES projected in 1986.

There is 157 m² (1690 ft²) of living area with a 9 m² (96 ft²) greenhouse and 57 m² (614 ft²) of south facing roof area.

The house is ALL ELECTRIC with a 2 1/2-ton heat pump and electric hot water heater.

The site layout has a detached garage with a lot area of 1/4 acre.
SYSTEM DESCRIPTION

- The system is grid connected with a 4.1 kW NOCT array rating using a GE rectangular SHINGLE MODULE ARRAY. The array consists of a total of 52 FULL AND 8 HALF MODULES COVERING 50 m² in a redundant parallel-series network.

- The power conversion subsystem uses a 4 kVA LINE COMMUTATED MAX POWER TRACKING INVERTER to convert dc generated power to ac. A 5 kVA SINGLE PHASE ISOLATION TRANSFORMER is used to match ac supply voltage to the load.

- The system operation is PARALLEL AND SYNCHRONIZED WITH THE UTILITY.

- Excess generated power is FED BACK to the utility.

- The system represents the SIMPLEST PHOTOVOLTAIC DESIGN with a minimum of components and controls.

![Utility Feedback System Diagram]
SYSTEM OPERATION

- The system has AUTOMATIC STARTUP and SHUTDOWN control.
- The system automatically shuts down with loss of the utility power.
- System operation is summarized by the sequence below:

1. At sunrise, in the automatic "on" mode, the ac and dc contactors will close when the array bus voltage reaches a threshold at 156 Vdc.
2. During the daylight period, the inverter operates continuously if there is a net power output.
3. The inverter will track the maximum power operating point within ±1 percent over the range of 156 to 160 Vdc.
4. The interruption of utility-supplied power opens the dc contactor and it remains open until the line voltage is restored.
5. At sunset, the inverter ac and dc contactors open when the net power output falls to zero. These contactors remain open throughout the night to eliminate the majority of the inverter parasitic losses.
PHOTOVOLTAIC ARRAY

- The array consists of SHINGLE PV MODULES connected in an 8 series by 7 parallel network covering 50 m² of roof area.
- The array orientation is due south with a roof pitch of 33.7°. The overall cell packing efficiency is 97% over the 50 m².
- The modules are DIRECT MOUNTED on top of the roofing felt and plywood roof sheathing. They form a weather tight roof.
- The modules are installed by an overlapping procedure similar to conventional shingles. Each shingle module requires two FCC butt terminations to electrically interconnect the module to the array. Standard roofing nails are used for attachment to the roof.
PHOTOVOLTAIC MODULES

- The module is currently under development by General Electric Company.
- The module uses 94 mm SQUARE SILICON CELLS, with 48 cells connected in series and 2 parallel circuits per module.
- A half-sized module with one series string of 36 cells is also used in the installation.
- For a NOCT of 65°C, the MAXIMUM POWER OUTPUT is 74 W and 16.6 V at SOC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).
- A summary of the module characteristics are:

<table>
<thead>
<tr>
<th></th>
<th>Full Module</th>
<th>Half Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module weight:</td>
<td>18 kg</td>
<td>9 kg</td>
</tr>
<tr>
<td>Total Cell area:</td>
<td>0.866 m²</td>
<td>0.433 m²</td>
</tr>
<tr>
<td>Exposed Module area:</td>
<td>0.916 m²</td>
<td>0.458 m²</td>
</tr>
<tr>
<td>Module packing factor</td>
<td>0.945</td>
<td>0.945</td>
</tr>
</tbody>
</table>
POWER CONVERSION SUBSYSTEM

- The PCS provides the interface between the PV array and the normal residential utility service and loads.
- The subsystem consists of three main components: the INVERTER, the DC FILTER and TRANSFORMER along with the associated control circuitry.
- The subsystem is rated at 4.0 kW of power output with a 5 kVA transformer, sized to accommodate the out-of-phase ac voltage and current.
- The subsystem characteristics are summarized in the table below.
- The Gemini Corporation of Mukwonago, Wisconsin, manufactures the subsystem components and Windworks, Inc., markets them.

KEY INVERTER DESIGN CHARACTERISTICS

Output Power Rating: 4.0 kW Continuous
Output Voltage: 240 Vac Utility Residential Service
Input Voltage: 168 ± 12 Vdc
Full Load Power Factor: 60% Minimum,
Full Load Efficiency: 92% Minimum
Full Load Harmonic Distortion: 30% Maximum
Operating Temperature: 0°C to 40°C
ARRAY SIZING

- The array sizing uses MARGINAL COSTS and BENEFITS.
- Energy sellback price the utility is willing to pay the homeowner affects the system sizing.
- The assumed energy escalation rate is 4% above inflation.

**BOSTON**

<table>
<thead>
<tr>
<th>Collector Area, m²</th>
<th>Life Cycle Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>20</td>
<td>1.2</td>
</tr>
<tr>
<td>40</td>
<td>1.1</td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
</tr>
<tr>
<td>80</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**MADISON**

<table>
<thead>
<tr>
<th>Collector Area, m²</th>
<th>Life Cycle Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.3</td>
</tr>
<tr>
<td>20</td>
<td>1.2</td>
</tr>
<tr>
<td>40</td>
<td>1.1</td>
</tr>
<tr>
<td>60</td>
<td>1.0</td>
</tr>
<tr>
<td>80</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**NOTES**

1. PRICE OF ELECTRICITY $0.0832/KWH
2. SELL BACK RATIO
   - 0.3
   - 0.5
   - 0.7
3. PRICE OF ELECTRICITY $0.0532/KWH
DESIGN PERFORMANCE

- Total net system output for both Boston and Madison is approximately 40% of the total load requirements.
- Overall system efficiency based on incident isolation for gross array area is approximately 8.3% for the Northeast.
INTEGRAL MOUNTED PV ARRAY FOR THE SOUTHEAST

A flat plate photovoltaic system with utility feedback is designed for a single story, all-electric house in the Southeast. The two major system elements are the photovoltaic array and the power conversion subsystem. Marginal life cycle cost analysis was used for system sizing. The analysis considers several values of array area and provides parametric results. The PV system is sized at 5.6 kW at NOCT conditions. The array covers the complete roof area and is integrally mounted in the roof. The 86 m² solar array uses a modified Solarex intermediate load module in a 7-parallel by 14-series module array.
The house design is for a SINGLE-STORY residence of NEW CONSTRUCTION for the SOUTHEAST region of the country.

The design includes PASSIVE SOLAR and ENERGY CONSERVATION FEATURES projected for 1986.

There is 161 m² (1736 ft²) living area with 92.2 m² (992 ft²) of south facing roof area.

The house is ALL ELECTRIC with a 3-ton heat pump and electric hot water heater.
The system is grid connected with a 5.6 kW NOCT rating using SOLAREX BLOCK IV INTERMEDIATE LOAD MODULES incorporated into an integral mount design. The array consists of 98 modules with 74.5 m² of aperture in a 7-parallel by 14-series network.

The power conversion subsystem (PCS) employs a 6 kVA-SELF COMMUTATED MAXIMUM POWER TRACKING INVERTER to convert PV generated power to ac and to match ac supply voltage to the load.

The system operation is PARALLEL and SYNCHRONIZED WITH THE UTILITY.

Excess generated power is FED BACK to the utility.
PHOTOVOLTAIC ARRAY

- The array consists of INTEGRAL MOUNTED PV modules connected in a 14-series by 7-parallel network covering 80 m² of roof area.

- The array orientation is due south with a roof pitch of 22.6°.

- The modules and mounting extrusions are mounted on the roof rafters and purlins. No plywood sheathing is used. The installation forms a weather-tight roof.

- Mounting extensions 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 patented connectors and factory supplied cables.
PHOTOVOLTAIC MODULES

- The module is manufactured by SOLAREX CORP., of ROCKVILLE, MARYLAND and was developed as part of the JPL Block IV procurement.
- The module uses Solarex 95 mm SQUARE CELLS with 36 cells connected in series and 2 parallel circuits for a total of 72 cells per module.
- For an estimated NOCT of 71°C, the MAXIMUM POWER OUTPUT is 56.9 W, and 13.0 V at SOC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).
- The design approach uses only the Solarex laminate assembly of the module. A specially designed frame is used to mate with the integral roof extrusions.

A summary of module characteristics include:

- Module weight: 15.9 kg
- Module packing factor: 0.80
- Total cell area: 0.650 m²
- Nominal size: 1.26 m long by 0.655 m wide
- Exposed installed module area: 0.815 m²

![Diagram of the module](image)
The Power Conversion Subsystem (PCS) provides the interface between the PV array and the normal residential utility service and loads.

The subsystem consists of three main components: the inverter, the dc filter and transformer, along with the associated control circuitry, packaged in a single unit.

The subsystem is manufactured by Abacus Controls, Inc., Sommerville, New Jersey.

The subsystem is sized for a 6 kW POWER OUTPUT with the transformer sized to accommodate the adjustment of the ac voltage and current.

The subsystem characteristics are summarized below.

**KEY INVERTER DESIGN CHARACTERISTICS**

<table>
<thead>
<tr>
<th>OUTPUT POWER RATING</th>
<th>6 kW CONTINUOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUTPUT VOLTAGE:</td>
<td>240 VAC Utility Residential Service</td>
</tr>
<tr>
<td>INPUT VOLTAGE:</td>
<td>200 ± 40 Vdc</td>
</tr>
<tr>
<td>FULL LOAD POWER FACTOR:</td>
<td>Unity</td>
</tr>
<tr>
<td>FULL LOAD EFFICIENCY:</td>
<td>90% Minimum (over 25% to 88% of operating range)</td>
</tr>
<tr>
<td>FULL LOAD HARMONIC DISTORTION</td>
<td>5% Maximum</td>
</tr>
</tbody>
</table>
ARRAY SIZING

- Energy sellback price the utility is willing to pay the homeowner affects overall system sizing.
- Sellback rates greater than 50% imply full roof arrays.
- The array sizing uses MARGINAL COSTS and BENEFITS.
DESIGN ELECTRICAL PERFORMANCE

- Net PV system output for Miami is 61% of the load requirements and the corresponding value for Charleston is 68%.

- For Miami, approximately 67% of the PV system output is applied directly to the house load while the utility receives the remaining energy. In Charleston, 53% is applied.

- The monthly net electrical system output in Miami is always less than the total monthly load.

- Overall average annual PV system efficiency, based on incident insolation for the gross array area, is 7% for this design in the Southeast. The corresponding peak module efficiency assumed is 8.8% at 28 degrees C.

14s x 7p CONFIGURATION

<table>
<thead>
<tr>
<th></th>
<th>ANNUAL TOTALS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIAMI</td>
<td></td>
</tr>
<tr>
<td>LOAD</td>
<td>14.9 MWh</td>
</tr>
<tr>
<td>PV SYSTEM OUTPUT</td>
<td>9.1 MWh</td>
</tr>
<tr>
<td>UTILITY MAKE-UP</td>
<td>8.8 MWh</td>
</tr>
<tr>
<td>SELL BACK</td>
<td>3.1 MWh</td>
</tr>
<tr>
<td>CHARLESTON</td>
<td></td>
</tr>
<tr>
<td>LOAD</td>
<td>12.7 MWh</td>
</tr>
<tr>
<td>PV SYSTEM OUTPUT</td>
<td>8.6 MWh</td>
</tr>
<tr>
<td>UTILITY MAKE-UP</td>
<td>8.2 MWh</td>
</tr>
<tr>
<td>SELL BACK</td>
<td>4.1 MWh</td>
</tr>
</tbody>
</table>
A PV SYSTEM FOR A TEMPERATE CLIMATE

A 4.3 kW grid-connected PV system with utility feedback is designed for a house having low space conditioning load requirements. The major system elements are the photovoltaic array and the power conversion subsystem. Marginal life cycle cost analysis was used for system sizing. The analysis considers various array sizes and provides parametric performance results. In general, with utility sellback rates of 50% or greater, the results indicate a PV array size as large as the available roof area.

This design considers a low energy consuming house with a minimum of available roof area. The design also provides a comparison of integral and stand-off mounting techniques for the same array configuration. The array is mounted on the garage roof which also is a different approach than previous designs.

The 40.3 m² solar array uses a laminated glass/cell assembly module in an array with four parallel circuits. Two circuits have 12 series modules and two circuits have 13 series modules.
HOUSE DESCRIPTION

- The house design is for a SINGLE-STORY residence of NEW CONSTRUCTION for a TEMPERATE CLIMATE region.
- The house can be sited following a ZERO-LOT-LINE plan.
- The design includes PASSIVE SOLAR and ENERGY CONSERVATION features projected for 1986.
- There is 142 m² (1530 ft²) of living space.
- The plan includes a TWO-CAR GARAGE with 44.4 m² (477 ft²) of garage roof area available for mounting the solar array.
**SYSTEM DESCRIPTION**

- The system is grid-connected with an 4.29 kW NOCT array rating using a glass laminate module assembly in an INTEGRAL and STANDOFF MOUNTING arrangement. The array consists of 50 modules covering 40.3 m².

- The power conversion subsystem uses a 4 kVA MAXIMUM POWER TRACKING INVERTER to convert dc generated power to ac and to match ac supply voltage and load.

- The system operation is PARALLEL AND SYNCHRONIZED WITH THE UTILITY.

- Excess generated power is FED BACK to the utility.

- The system has automatic STARTUP AND SHUTDOWN control and shuts down with loss of the utility.

- System operation is summarized by the sequence below:

  1. At sunrise, in the automatic mode, when the input voltage exceeds 180 V, the ac line contactor is closed and the phase locked loop and maximum power tracker are energized.

  2. During the daylight period, the inverter operates until the dc input voltage falls below 160 V.

  3. The inverter tracks the maximum power point within ±1% over the range of 160 to 240 Vdc.

  4. The interruption of utility supplied power opens the ac contactor and it remains open until the line voltage is restored.

  5. At sunset, the inverter ac contactor opens when the net power output falls to zero. This contactor remains open throughout the night to minimize parasitic losses.
PHOTOVOLTAIC ARRAY

- The array consists of PV modules and mounting accessories which may be used either as an INTEGRAL MOUNT or as a STANDOFF MOUNT. There are 4 circuits connected in parallel with two 13 series circuits and two 12 series circuits.

- The array orientation is due south with a roof pitch of 18.4°.

- The modules are mounted on a series of channel supports which can be placed on the roof truss system for an integral mount or on the shingled roof for a standoff mount. Electrical connections are made with patented connectors and factory supplied cables.

- The watertight integrity of the photovoltaic roof is assured by a simple module perimeter seal which uses the sloping roof surface to the maximum advantage. An overlapping seam is used between modules to shed water which runs down the roof surface.
PHOTOVOLTAIC MODULES

- The module assembly is a laminated glass superstrate/cell unit similar to the Solarex Corporation, Block IV residential module, but with sealant strips attached for mounting.
- The module uses nominal 100 mm square cells with 36 series units of 2 parallel cells for a total of 72 cells per module.
- For an estimated NOCT of 71°C the maximum power output is 85.8 W at 13 V at SOC conditions (1 kW/m², 20°C ambient, 1 m/s wind speed).
- A summary of module characteristics include:
  - Module weight = 11.69 kg
  - Total cell area = 0.72 m²
  - Exposed module area = 0.8045 m²
  - Module packing factor = 0.895
POWER CONVERSION SUBSYSTEM

- The Power Conversion Subsystem (PCS) provides the interface between the PV array and the normal residential utility service and loads.

- The subsystem consists of three main components: the inverter, the dc filter and transformer, along with the associated control circuitry, packaged in a single unit.

- The subsystem is manufactured by Abacus Controls, Inc., Sommerville, New Jersey.

- The subsystem is sized for a 4 kW POWER OUTPUT with the transformer sized to accommodate the adjustment of the ac voltage and current.

- The subsystem characteristics are summarized below.

**KEY INVERTER DESIGN CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Output Power Rating</th>
<th>4 kW Continuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Voltage:</td>
<td>240 Vac Utility Residential Service</td>
</tr>
<tr>
<td>Input Voltage:</td>
<td>200 ± 40 Vdc</td>
</tr>
<tr>
<td>Full Load Power Factor:</td>
<td>Unity</td>
</tr>
<tr>
<td>Full Load Efficiency:</td>
<td>90% Minimum (over 25% to 88% of operating range)</td>
</tr>
<tr>
<td>Full Load Harmonic Distortion</td>
<td>5% Maximum</td>
</tr>
</tbody>
</table>

![Diagram of Power Conversion Subsystem](image)
The array sizing uses MARGINAL COSTS and BENEFITS.

The system shows economic viability (LCCR < 1) with sellback rates of 30% or greater. These sellback rates imply full roof arrays.

---

**ARRAY SIZING**

- The array sizing uses MARGINAL COSTS and BENEFITS.
- The system shows economic viability (LCCR < 1) with sellback rates of 30% or greater. These sellback rates imply full roof arrays.

---

**ARRAY CONFIGURATION**

<table>
<thead>
<tr>
<th>Collector Area - m²</th>
<th>PS/PE = 0.3</th>
<th>0.5</th>
<th>0.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>13S x 2P + 12S x 2P</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SANTA MARIA**

**GARAGE ROOF AREA**

---

**COLLECTOR AREA - m²**

---

3-60
DESIGN ELECTRICAL PERFORMANCE

- Net PV system output for Santa Maria, CA is 67% of the load.
- Performance results indicate that 56% of the PV system output is applied directly to the house load while the utility receives the remaining energy.
- Overall PV system efficiency based on incident insolation for gross array area is 9.6% for Santa Maria.

![Graph showing monthly energy and annual totals for Santa Maria load, PV system output, and array configuration.]

**SANTA MARIA**

**LOAD**

**PV SYSTEM OUTPUT**

**ARRAY CONFIGURATION**

13S x 2P + 12S x 2P

**ANNUAL TOTALS**

- LOAD: 11.3 MWh
- PV SYSTEM OUTPUT: 7.6 MWh
- UTILITY MAKE-UP: 7.1 MWh
- SELL BACK: 3.4 MWh
 SECTION 4
DESIGN CONCERNS

During the design effort, several concerns were addressed. Some of the design considerations were only pertinent to a single design, but others were applicable to all of the designs. All of these are summarized in the following sections.

Array Sizing

The primary area available for residential PV arrays is roof area. In grid-connected applications, the system size should be selected to deliver energy to the owner's load at the minimum life-cycle cost, including the cost of backup utility energy. Assuming 1986 array costs of 70¢/kWp and 1986 system costs, study results indicate array areas using all of the available roof area when sellback rates are 50% or greater. Incorporating cost effective passive house design features and energy conservation features reduces the overall household energy requirements and thus reduces the array requirements. This allows more flexibility in the architectural house design. Additional background information into system sizing considerations is provided in Reference 1.

Roof Constraints

The physical size or available dimensions of the roof can impose several constraints on the array configuration. This is more of a problem for direct mounting systems where arbitrary row wiring may not be possible; however, cross row wiring in integral or standoff mountings make the installation details more difficult and more costly.

Rectangular areas are desirable both from an aesthetic viewpoint and from an electrical interconnect standpoint. If modules are only connected in series up the slant height of the roof, the system operating voltage is limited to, at a minimum, multiples of the slant height. This implies that, for different roof sizes using the same modules, each system results in a different operating voltage. A transformer may be required to ultimately match house loads. The addition of a transformer to match the loads appears more practical and less costly than changing the specifications for the inverter package for each voltage input. Thus, a common operating voltage range is difficult to standardize. Similar concerns result if the modules are connected in series along the roof length. Reference 9 addresses the problem of roof constraints in more general terms.
Array Mounting Approach

Each of the key array mounting approaches, except rack mounting, was addressed. It is not apparent from the designs which approach is the most cost effective technique. Indeed, each approach has its advantages and disadvantages. It is important to note, however, that the array mounting technique has subtle effects on the system overall costs. Module interconnection layouts, array operating voltage, replacement or maintenance access, and weather seals all impact the system. Some of these cost impacts will be evaluated as Sandia obtains detailed cost estimates for each of the developed designs. In addition, the data being generated at the Northeast and Southwest Residential Experiment Stations (RES) will also provide guidance in array mounting approach performance and costs.

Power Conversion Subsystem

Several design concerns exist in the area of power conversion. Experience at the RES's have indicated problems in startup and maximum power tracking. The designer must be aware of the high open circuit voltage that can exist during startup conditions when there is a low total power output. The specifications of the unit must accommodate these initial conditions.

It is easy to specify Power Conversion Subsystem operation with ranges within a few percent of the maximum power point; however, test data on maximum power tracking options, has indicated difficulty in achieving these specifications. Alternate schemes are under development, including the use of a pilot cell. This approach is an open loop control algorithm and, although relatively simple, may not represent the true array operating point over the lifetime of the system as module performance is degraded due to dirt, electrical problems or shadowing. Thus, additional development is required on these units.

Throughout the study, two primary types of power conversion units were available, the Gemini and the Abacus Sunverter. During this time period, Abacus was also developing a lower cost version of the currently available unit. This unit was specified in several of the designs. After the designs were completed, however, Abacus changed their development directions and this design version was dropped from further development. In addition, residential sized development of power conversion units was underway by several other firms. Optimal inverter conceptual designs have been developed by United Technologies Corporation, Westinghouse, General Electric and Airsearch Manufacturing Company (Division of Garrett), under
DOE contract. DECC, Delta Electronic Control Division of Helionetics, Inc. and American Power Conversion Corporation also have hardware either presently available or to be available in the near future. Sandia is also developing a baseline inverter specification. Thus the state-of-the-art in power conversion equipment will be changing over the next several years and manufacturers should be consulted for the latest available information.

Isolation Transformer and Grounding

In many of the designs, the negative busbar was located along the eave of the roof. The negative array busbar located near the gutters at the eave of the roof is subjected to a potential ice buildup from the gutter under a combination of environmental circumstances in northern installations. Water from this ice backup could conceivably penetrate the insulation of the busbar or a slender tool being used to clean debris or the ice blockages could come in contact with the busbar providing a potential to ground. A wired connection to earth ground for the negative busbar should be provided as an additional safety precaution. This connection creates the requirement for an isolation transformer in the power conversion system. While an isolation transformer is not a mandatory system element except for array bus grounding, its presence can provide a convenient location for adjustments of system output to the required house service rating. This feature provides design flexibility in array circuit layout for different roof designs. The transformer, however, adds economic penalties both in initial cost and in net power loss over the life of the system operation. Elimination of array bus grounding and the associated isolation transformer, providing the array output matches the house service rating, can increase the system output at negligible decrease of safety.

Exterior Disconnect Switches

Almost all of the designs had a fused exterior switch and an interior switch. The external switch allows to open circuit the array in the event of fires, etc. It is a redundant switch and, in some measure, tends toward a conservative design approach. The additional devices and installation, however, are only minor additional initial economic penalties. Non-functional redundancy in this chain may be eliminated as experience with system installations is gained and NEC codes for photovoltaic installations are developed.
Battery Location Concerns

Location of batteries within a residence presents several concerns. Trade-offs between an interior and exterior location for the batteries resulted in the interior location based primarily on the requirements for maintaining environment control and access for maintenance. The batteries were placed in the equipment room with all the PV and conventional equipment.

The room must be designed to have sufficient ventilation to remove any hydrogen buildup, to accommodate active battery ingredients spillage and to minimize access to the equipment from unsuspecting occupants, especially children. To prevent a hydrogen buildup within the room, a guaranteed amount of ventilation at all times is required to dissipate the small amounts of hydrogen and chemicals emitted under normal operating conditions and a positive 30-60 cfm ventilation is suggested to remove hydrogen during equalization of battery charge. These ventilation requirements result in a slight increase in infiltration loss in the house. To accommodate any possible spillage, a 5 cm drop in the slab should be designed around the battery racks. To minimize general access to the batteries, they can be located in a metal enclosure. The cabinet should be heavily louvered and have a locked door. All of these design considerations increase system costs. As storage systems become more widespread, standard designs to resolve these concerns may be developed.

Module Interconnection

Several of the module interconnection schemes do not currently satisfy the National Electric Code. For example, the AMP flat conductor cable used for the direct mount shingle designs is currently in the codes for interior, commercial under-carpet installations only. The wire runs between battens of the direct mount batten module also would not be classified as raintight raceways, since the conductors are not enclosed on all sides. In addition, splice connections would not be allowed within the batten seams. These apparent code restrictions have to be resolved for widespread implementation.

Fire Safety

Fire safety is an important issue that could not be specifically addressed in the design other than for general considerations. It is likely that the module installations will be considered as a roof covering by local building code
officials. In this case, the module installation must receive a fire rating classification in conformance with the requirements of UL-790, "Test for Fire Resistance of Roof Covering Materials".

Local fire companies would have to be alerted and instructed in regards to the potential danger of the energy-producing roof. The location of the dc power line adjacent to the normal utility line and the exterior disconnect switch should alert fire personnel that the house has an additional power supply. However, fire personnel must be informed that disconnect at the switch still leaves the roof as an active generator in the daylight and only interrupts power supply to the house.
SECTION 5
DESIGN STUDIES

This section discusses some design studies which were applicable to the designs in general or were completed after the respective report was written. For example, power conversion subsystem requirements were evaluated relative to operating voltage ranges and losses associated with restricted voltage operation ranges through system simulations. A correlation for estimating power losses for limited system operation within specific voltage ranges was developed. In addition, annual distributions of array current characteristics were developed.

Power Conversion Subsystem Correlations

During system analyses of the detailed designs, narrowing the maximum power tracking operational voltage range over which the power conditioner operates was found to have only small effects on the total annual energy collected. In fact, single voltage operation in some cases might be implied. However, the amount of lost energy and voltage point of minimum energy loss vary with several parameters. Thus, attempts to correlate the data were made.

Initially, a series of curves showing the difference in energy loss ($E_V$) (for a restricted voltage range) from the maximum available (maximum power tracking without limitations, $E_{MP}$) versus operating voltages were generated. Figure 5-1 shows a typical curve for Miami. The percent energy loss was determined from the expression $\frac{E_{MP} - E_V}{E_{MP}}$ which is the ordinate in the figure.

One curve represents losses incurred when the array voltage is limited on the lower end of the voltage range from 180V to 220V. This means that the system was constrained to operate at maximum power up to a specific voltage and then limited to that voltage if the maximum power point was above it. Therefore, as the range of maximum power voltage operation is increased, the loss of collected energy over that collected for unconstrained maximum power tracking decreases. The second curve demonstrates the effect of limiting the voltage on the high end from 220V to 180V. A minimum of three simulation runs were required to establish each curve, and the point of intersection denotes the minimum loss voltage. Plots of this type were generated for several locations, and provided an adequate data base to attempt correlations. It was intended that such correlations would
establish the minimum loss voltage and corresponding losses and thereby eliminate the need to generate six computer runs. Note that a voltage range, V, can be defined around the minimum loss point.

Figures 5-2 through 5-6 show similar curves for different locations and different array configurations. Several types of panels were simulated utilizing vendor IV characteristics, including the GE Block IV and rectangular shingle designs, the ARCO-SOLAR Block IV batten module and the Solarex Block IV module. The locations for the analyses were Boston, Phoenix, Santa Maria, Miami and El Paso.

Available simulation data of the residential PV systems was screened to establish correlating parameters. The NOCT temperature and voltage at NOCT conditions were obtained by modelling, or from vendor data. With this information, attempts were first made to correlate minimum loss voltage, normalized by the NOCT voltage with insolation. Figure 5-7 shows relatively good correlation between the minimum loss voltage ($V_{ML}$) normalized to the NOCT voltage ($V_{NOCT}$) with the total insolation ($I$) incident on the module, normalized to a reference insolation ($I_{REF}$). The worst deviation is 5% from the average curve fit.

Figure 5-1. System Losses for the Southeast Design as a Function of Limiting Voltage Range
Figure 5-2. System Losses for Boston, Design 1.

Figure 5-3. System Losses for Phoenix, Design 1.
Figure 5-4. System Losses for Boston, Design 4.

Figure 5-5. System Losses for Santa Maria, Design 6.
Figure 5-6. System Losses for El Paso Single Family

Figure 5-7. Comparison Between Minimum Loss Voltage and Insolation.
Figure 5-8 shows the correlation of the same voltage ratio $(V_{ML}/V_{NOCT})$ with average ambient temperature normalized to the NOCT temperature ($T_{NOCT}$). Again, a relatively good correlation is achieved with a $3\%$ deviation of the average fit.

Once the minimum loss voltage was determined, the energy loss effects of constraining the maximum power tracking range were correlated. The correlating parameter was the ratio of the energy loss from full maximum power tracking for a $\Delta V$ operating range $(E_{MP} - E_{\Delta V})$ to the maximum energy loss at the minimum loss voltage $(E_{MP} - E_{ML})$. This ratio ranges from 0 to 1 and is plotted versus the normalized contained voltage operating range $(\Delta V/V_{NOCT})$. Figure 5-9 shows the correlation.

An example illustrates the use of these correlations to determine the fixed voltage minimum energy loss point, $V_{ML}$, and the constrained operating voltage energy loss, $E_{\Delta V}$. Assume the following:

- **Location**: Phoenix, $I = 6560$ wh/m$^2$-day
- **Array Area**: 93 m$^2$
- $V_{NOCT}$: 183 V
- $\Delta V$: 10 V

For these assumptions, the parameter $I/I_{REF}$ is 1.09. Using Figure 5-7, the ratio $(V_{ML}/V_{NOCT})$ is 1.04. Thus, the operational voltage point for minimum energy loss from full maximum power tracking for a Phoenix location is 190 V.

Computer simulations can be made to establish the annual collected energy at full maximum power tracking, $E_{MP}$, (17.5 MWh for this example) and the energy collected at the fixed voltage minimum loss point, $E_{ML}$ (17.15 MWh for this example).

Thus, for a constrained operating voltage range of $\pm V = 10$ V around the minimum loss voltage point $\frac{\Delta V}{V_{NOCT}} = 0.055$ and Figure 5-9 gives

$$\frac{(E_{MP} - E_{\Delta V})}{(E_{MP} - E_{ML})} = 0.78$$

Solving for $E_{\Delta V}$ provides the estimate of the energy loss from full maximum power tracking of 17.23 MWh or a 1.5% energy loss.
Figure 5-8. Correlation Between Minimum Loss Voltage and Normalized Ambient Temperature

Figure 5-9. Correlation Between Normalized % Increase in Loss with Normalized Voltage Operating Range about Minimum Loss Voltage.
Sensitivity of Photovoltaic Module Performance to Roof Insulation for the Integral Mount Configuration

A parametric study was conducted to determine the performance sensitivity of an integrally mounted photovoltaic module to roof insulation and ambient conditions. In the analysis, an attic temperature profile was assumed as two piecewise continuous linear functions of ambient temperature. Results generated using a one-dimensional Fourier conduction approach indicate that the backface insulation has little (<5%) effect on module performance, and the highest module efficiency is achieved for the case of no insulation.

The cell temperature has a significant impact on PV module performance, and this necessitates the use of an accurate technique for predicting collector heat loss. Reference 10 provided equations for radiative heat loss while the convective heat loss relations were furnished by Reference 11. A simple one-dimensional Fourier approach provided a means of establishing the effective conductance from the solar cell to the attic. A cross section of the PV module is illustrated in Figure 5-10 which shows this thermal path, and Table 5-1 presents the corresponding material and geometric properties. An energy balance was written for the module in terms of the front face and back face heat losses, and a Newton-Raphson method provided a solution for cell temperature.

The backface heat loss is expressed as:

\[ Q_b = C_{\text{eff}} (T_{\text{CELL}} - T_{\text{attic}}) \]  

(1)

where \( C_{\text{eff}} \) is the effective conductance from the cell to the attic and \( T_{\text{attic}} \) is the attic temperature. Two piecewise continuous linear profiles, as shown in Figure 5-11, were assumed for \( T_{\text{attic}} \) as a function of outdoor ambient temperature.

The net front face heat transfer expression is:

\[ Q_f = Q_{\text{ABS}} - 0.8 \times 5.6697 \times 10^{-8} (T_{\text{CELL}}^4 - T_{\text{SKY}}^4) \]

\[ - 1.247 \times (T_{\text{CELL}} - T_{\text{AMB}}) \times \cos (\theta_f)^{1/3} (T_{\text{CELL}} - T_{\text{AMB}}) \]

\[ + 3.81 \times V_{\text{WIND}} \quad (W/m^2) \]

where \( Q_{\text{ABS}} \) is the amount of solar energy absorbed by the collector and \( \theta_f \) is the collector tilt angle with respect to the horizontal.
Figure 5-10. Module Cross Section for Integral Mount Configuration

Table 5-1. Material Combinations for Thermal Path from Solar Cell to Attic

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>h (W/m²·°C)</th>
<th>k (W/m²·°C)</th>
<th>R (m²·°C)/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVA</td>
<td>0.508</td>
<td></td>
<td>1.64</td>
<td>0.001</td>
</tr>
<tr>
<td>TEDLAR</td>
<td>0.051</td>
<td>5.68</td>
<td>0.475</td>
<td>0.00035</td>
</tr>
<tr>
<td>AIR GAP</td>
<td>2.54</td>
<td></td>
<td></td>
<td>0.063</td>
</tr>
<tr>
<td>POLYURETHANE INSULATION</td>
<td>25.4</td>
<td></td>
<td>1.08</td>
<td>0.77</td>
</tr>
<tr>
<td>AIR GAP</td>
<td>2.54</td>
<td>5.68</td>
<td></td>
<td>0.063</td>
</tr>
<tr>
<td>ALUMINUM BACK PLATE</td>
<td>1.016</td>
<td></td>
<td>750</td>
<td>5.2 x 10⁻⁶</td>
</tr>
<tr>
<td>AIR-NATURAL CONVECTION</td>
<td></td>
<td>9.1</td>
<td></td>
<td>0.11</td>
</tr>
</tbody>
</table>
The energy balance is:

\[ Q_b - Q_f = 0 \]  \hspace{1cm} (3)

which provides a steady state solution for \( T_{\text{CELL}} \).

Figure 5-12 shows the effects of wind velocity and ambient temperature upon cell temperature and module efficiency for 1 kW/m\(^2\) incident and R-4 insulation. Both ambient temperature and wind speed are observed to have a significant effect.

The sensitivity of cell temperature and efficiency to roof insulation is presented in Figure 5-13. The amount of insulation varies from 0 to R-26 (approximately 6" thick), and the greatest influence occurs as the wind velocity decreases to 0 m/s. The effect on efficiency is less than a 5\% reduction as \( R \) is increased, and very little effect is observed at the higher wind speeds. This indicates that the front face heat loss is more dominant than that of the backface for the integral mount configuration.

The results of the analysis established the following conclusions:

1. Roof insulation affected module performance by less than 5\%.
2. Front face heat loss was more significant than backface losses.
3. Wind and ambient temperature may affect performance by as much as 20\%.

This analysis can also apply to a direct mounted array with insulation in the attic ceiling.

**Alternate Battery System Shunt Analysis**

The design of the battery system in the Southwest was developed so that when the battery was fully charged and the load was supplied, waste energy would be shunted to ground. A possible option of utilizing this energy was to direct it to a resistive heating element in the domestic hot water tank, thus, using the hot water tank as an additional storage element. In effect, however, as energy is directed and stored in the hot water tank, the total house load is reduced and, thus, additional waste energy is generated. A quantitative evaluation of usable energy was performed based on the system analysis results presented in Reference 5. The design analysis predicted an excess energy of 1.0 MWh in Albuquerque for an array configuration of 65 m\(^2\) of active cell area and a battery capacity of 25 kWh. Almost all of this occurs in the spring and fall seasons. In order to establish how much of this energy could be utilized, typical hourly hot water demand profiles used in the analysis were examined. The hourly profiles of
$$T_{ATTIC} = 2.667 T_{AMB} - 28.33°C$$

$$T_{ATTIC} = T_{AMB} + 5°C$$

Figure 5-11. Assumed Attic Temperature as a Function of Ambient Temperature

Figure 5-12. Cell Temperature and Module Efficiency as a Function of Ambient Conditions for the Integral Mount Configuration
available excess energy were also constructed and superimposed on the demand profiles. Figure 5-14(a) illustrates the amount of PV array excess energy available for a typical spring day. Note that the battery is not fully charged until noontime. Between noon and 5 o'clock, there are 16.5 kWh of excess energy present and approximately 16.0 kWh are effectively transferred to a pre-heat water tank. A two-tank system was considered for simplicity in this analysis. The corresponding hot water usage is shown in Figure 5-14(b). The hourly pre-heat tank temperature is shown in Figure 5-14(c). As the excess energy is input, the temperature steadily rises until the maximum tank temperature of 76.7°C is reached. This stored thermal energy is sufficient to supply a substantial portion of the hot water load during the evening peak hours and beyond. On a daily basis in springtime, 47% of the hot water load can be provided by usage of available excess energy.

Similar results exist for the fall season. If all of the energy transferred to the hot water system is used prior to the start of excess energy availability,
NOTES:
1. ARRAY CONFIGURATION
   10S X 10P
   65 m² CELL AREA

2. BATTERY CAPACITY
   20 KWH

---

Figure 5-14. Available Power, Hot Water Usage, and Preheat Tank Temperature for a PV System in Albuquerque
the next day no additional waste energy is generated. If, however, the hot water storage displaces loads during PV system output, additional waste energy may be generated.

Overall, this option does provide a means of utilizing waste energy.

System Current Characteristics

In all of the designs, annual distribution of the array voltage and power characteristics were generated to predict power conversion subsystem requirements. The current characteristics were not, however, usually reviewed. It is feasible that under certain weather conditions, array current output could be above power conversion equipment limits. Thus the annual distribution of current was calculated and plotted for several designs. Figure 5-15 shows the hours of operation for current level for the sixth system design in Santa Maria. A peak current output of 26 Amps is noted. Figures 5-16 and 5-17 show similar curves for the fourth design in Boston and Madison. Typical annual current distributions at or below system power levels were also determined for the fourth design as evidenced in Figures 5-18 and 5-19 for Boston and Madison. These curves defined maximum current requirements of power conditioning equipment and estimate the amount of energy output occurring at the current levels.
Figure 5-15. Current Duration for the Sixth Design, Santa Maria, CA.

Figure 5-16. Current Distribution for the Fourth Design, Boston

NOTES:
1. ARRAY CONFIGURATION 56
   RECTANGULAR SHINGLES 85 X 7P
NOTES:
1. ARRAY CONFIGURATION
   56 RECTANGULAR SHINGLES
   8S X 7P

3580 HOURS

Figure 5-17. Current Duration for the Fourth Design PV Array, Madison

NOTES:
1. ARRAY CONFIGURATION
   56 RECTANGULAR SHINGLES
   8S X 7P

33.6 AMP

6.4 MWH

Figure 5-18. Current Distribution as a Function of Solar Array Energy for Boston
Array Open Circuit Voltage

Many of the designs developed used the array open circuit voltage as the condition for start-up. Some early test data from the Northeast and Southwest Residential Experiment Stations indicated that actual open circuit voltages could exceed power conversion equipment limits under certain weather conditions. Thus for the temperate climate design in Santa Maria, Reference 8, the open circuit voltage was plotted for several weather conditions. Figure 5-20 shows these results. The array NOCT voltage is 185V. A curve similar to this figure helps to identify maximum array open circuit voltage that may exist for a given array configuration and should be investigated to assure system operation within the power conversion subsystem limitations.
Figure 5-20. Effects of Ambient Temperature and Solar Intensity on Open Circuit Voltage
SECTION 6
REFERENCES


12. G. Darkazalli, "A Description of the University of Texas at Arlington Solar Energy Research Facility Photovoltaic/Thermal Residential System," MIT-Lincoln Laboratory, C00-4577-5, March 16, 1979


APPENDIX A
SUMMARY OF SYSTEM CONFIGURATION EVALUATIONS
APPENDIX A
SUMMARY OF SYSTEM CONFIGURATION EVALUATIONS

PV ONLY SYSTEMS

System I(a) All Electric System/Battery Storage

Block Diagram

![Block Diagram]

Description

This system involves all-electric loads with space heating and cooling provided by a heat pump. The PV system includes batteries connected directly across the solar array bus, with the solar array operating point established by the voltage of the battery. Battery charge control is accomplished by limiting the battery charge voltage to a prescribed level. Control is exerted by partial shunting of discrete sections of the solar array current to limit battery charge voltage. Excess battery temperature is also limited by shunting out array sections. Battery discharge control is only exerted when the battery has been almost depleted, as indicated by a lower discharge voltage limit. When this occurs, the transfer of power through the inverter is interrupted completely and is not restored until the battery is fully charged. This would occur when the upper charge voltage limit is reached. The inverter supplies power up to its rated limit. Any demand in excess of this limit is supplied by direct tie-in to the utility.

Variations of this basic system involves, (1) utilization of excess PV energy for useful auxiliary heating (e.g., domestic hot water) in place of wasteful dissipation through the shunt and (2) nighttime utility charging of the batteries where advantage can be taken of lower nighttime rates.
Studied By

- General Electric (References #15, #16, and #17)
- Martin Marietta (Reference #21)
- Westinghouse (Reference #18)
- MIT-Lincoln Lab. (Reference #14)

Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>No max power tracker</td>
<td>Initial cost and maintenance of batteries</td>
</tr>
<tr>
<td>Does not require feedback to utility</td>
<td>Energy dissipated through shunt when PV system output exceeds what load and battery will accept</td>
</tr>
<tr>
<td></td>
<td>Energy losses through battery heat dissipation</td>
</tr>
<tr>
<td></td>
<td>Digital shunt and battery charge control devices required</td>
</tr>
<tr>
<td></td>
<td>Somewhat lower annual energy displacement than no battery system</td>
</tr>
<tr>
<td></td>
<td>Battery generated hydrogen gas explosive hazard. Cost of safety features to meet local codes</td>
</tr>
</tbody>
</table>

Conclusions

This PV only system is less economical and displaces less energy than a system without battery storage utilizing a maximum power tracker and utility feedback. Major factors contributing to disadvantage of this system include cost of battery storage and the losses associated with the charge/discharge cycles.

Though applicable to all regions, this system proved most cost effective in high insolation areas, providing a significantly larger percentage of electrical load, for example, in Phoenix than in Boston. A considerable battery development effort is of course necessary to meet battery projected 1986 cost and technical goals.
System I(b) All Electric/Feedback

Block Diagram

Description

This system involves all-electric loads, with space heating and cooling provided by a heat pump. The PV system includes a maximum power tracking inverter and permits feedback of excess PV energy to the utility grid connected in parallel with the photovoltaic system. The utility distribution system essentially becomes the storage medium for the residential PV system. When PV maximum power output is less than load demand or during nighttime periods, power is supplied by the utility.

Since the inverter AC power output is synchronized with the utility back-up source, any loss of utility power results in interruption of the inverter operation. This interruption is necessary to prevent excess array output from damaging residential loads through over-voltage.

Studied By

- General Electric (References #15, #16, and #17)
- Martin Marietta (Reference #21)
- Aerospace (Reference #22)
Conclusions

Advantages

• Simplest system

• Utility essentially acts as electrical storage medium for all excess energy generated by PV array

Disadvantages

• Acceptance of feedback by utility

• Low buy-back rate makes system less attractive

This system is the least complex to implement, assuming of course, utility acceptance of excess PV array output. Large scale sell-back of power to the utility from many residences can pose a serious problem to the utility.

Of the PV only systems investigated, the feedback system provided the highest energy displacement for an all-electric residence. Besides being appropriate for all regions, it provided higher performance and cost effectiveness than PV only systems with batteries.

System I(c) Fossil Heating/Feedback

Block Diagram
Description

This system involves the general household electrical loads and an electrically driven vapor compression space cooling unit. Domestic hot water and space heating are provided by a fossil fuel fired furnace. This PV system is identical to system Ib, having a maximum power tracking inverter and feedback of excess energy to the utility grid.

Studied By

- General Electric (Reference #16)
- Aerospace (Reference #22)

Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Utility essentially acts as electrical</td>
<td>• Acceptance of feedback by utility</td>
</tr>
<tr>
<td>storage medium</td>
<td>• Economic viability</td>
</tr>
<tr>
<td>• Simple system</td>
<td>dependent on buy-back rate</td>
</tr>
<tr>
<td></td>
<td>• PV cannot be used directly for heating</td>
</tr>
</tbody>
</table>

Conclusions

This system proved only slightly less economical than the PV only feedback system Ib. Thus, either back-up energy form, electrical or fossil, can effectively be accommodated by the PV only systems.

Fossil fuel fired burners providing space heating and hot water are primarily applicable in the cold and moderate (hot/cold) climate regions where they are predominantly in use today.
System I(d) All Electric/Battery Storage/Max. Power Tracking

**Description**

This system involves an all-electric load, with space heating and cooling provided by a heat pump. The PV system includes a pulse width modulated (PWM) down converter/maximum power tracker in series with the inverter, and battery storage under control of a battery charge controller. The PV system operates at maximum power, unless the output exceeds the load and battery requirements. At this point, the duty cycle of the PWM automatically decreases to move the system operating voltage toward the open circuit voltage of the array until the available source power is equal to the total power demand of the load and batteries. The utility tie-in permits grid power to supplement PV maximum power output when load demands exceed the photovoltaic system output.

A variation of this system is the placement of the pulse width modulated converter/maximum power tracker in the charge leg of the batteries (i.e., in parallel with the inverter). Therefore, PV power can pass directly to the inverter and on to the load without passing through the PWM/maximum tracker. Only PV power to the batteries passes through the PWM/maximum power tracker. With this system, maximum power tracking takes place only during periods of battery charging. During the sunrise and sunset periods of the day, when some load sharing battery discharge is required, the solar array bus voltage is clamped to the battery discharge voltage and the maximum power tracking battery charge regulator is disabled. Maximum power tracking takes place when array output...
capability exceeds the load demand. However, as with the series system, if the total available power at the array maximum power point is greater than what the inverter and batteries will accept, the duty cycle of the PWM regulator automatically decreases to move the system operating voltage toward the open circuit voltage of the array until the available source power is equal to the total power demand of the load and batteries. When the load demand exceeds the power available from the solar array, the batteries discharge, and as previously indicated clamps the DC bus voltage to the battery discharge voltage, forcing operation at a voltage considerably less than the solar array maximum power voltage.

**Studied By**

- General Electric (Reference #17)
- Martin Marietta (Reference #21)

**Advantages and Disadvantages**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Potentially higher system output with power tracker for battery storage systems</td>
<td>• Increased control complexity</td>
</tr>
<tr>
<td>• Does not require feedback to utility</td>
<td>• Cost of additional equipment</td>
</tr>
<tr>
<td></td>
<td>• Higher losses</td>
</tr>
</tbody>
</table>

**Conclusions**

These systems with battery storage and maximum power tracking, are higher cost configurations and displace less energy than either the battery/shunt system (1a) or maximum power tracking/feedback system (1b). Therefore, they provide no significant improvement or advantage over these other PV only systems.

**Comparison Evaluation of PV Only Systems**

A comparative evaluation of each of the PV only systems against a set of criteria previously described in Section 2.0, is presented in Table A-1. The evaluation resulted in the following rankings of PV only systems.

<table>
<thead>
<tr>
<th>Rank</th>
<th>System Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ib, All Electric/Feedback</td>
</tr>
<tr>
<td>2</td>
<td>Ia, All Electric/Battery</td>
</tr>
<tr>
<td>3</td>
<td>Ic, Fossil Heating/Feedback</td>
</tr>
<tr>
<td>4</td>
<td>Id, All Electric/Max. Power Tracking/Battery</td>
</tr>
</tbody>
</table>
### TABLE A-1. COMPARISON EVALUATION OF PV-ONLY SYSTEMS

<table>
<thead>
<tr>
<th>SELECTION CRITERION</th>
<th>SYSTEM I(a)</th>
<th>SYSTEM I(b)</th>
<th>SYSTEM I(c)</th>
<th>SYSTEM I(d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECONOMIC/PERFORMANCE RESULTS</td>
<td>FAIR</td>
<td>GOOD</td>
<td>FAIR</td>
<td>FAIR - POOR</td>
</tr>
<tr>
<td>CURRENT TECHNOLOGY STATUS</td>
<td>FAIR</td>
<td>FAIR</td>
<td>FAIR</td>
<td>FAIR</td>
</tr>
<tr>
<td>PROJECTED STATUS FOR 1986</td>
<td>FAIR - GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>FAIR</td>
</tr>
<tr>
<td>DEVELOPMENT RISK</td>
<td>FAIR - GOOD</td>
<td>GOOD</td>
<td>GOOD</td>
<td>FAIR</td>
</tr>
<tr>
<td>SYSTEM COMPLEXITY</td>
<td>FAIR</td>
<td>GOOD</td>
<td>GOOD</td>
<td>POOR</td>
</tr>
<tr>
<td>PROJECTED SYSTEM COST</td>
<td>FAIR</td>
<td>GOOD</td>
<td>GOOD</td>
<td>FAIR</td>
</tr>
<tr>
<td>REGION APPLICABILITY</td>
<td>GOOD</td>
<td>GOOD</td>
<td>FAIR - GOOD</td>
<td>GOOD</td>
</tr>
<tr>
<td>DUPLICATION OF SYSTEM COMPONENTS</td>
<td>GOOD</td>
<td>FAIR - GOOD</td>
<td>FAIR</td>
<td>FAIR</td>
</tr>
</tbody>
</table>

| RANKING | 2     | 1     | 3     | 4     |
This system involves all electrically driven loads with solar thermal energy used to supplement space and hot water heating. A heat pump provides the space heating and cooling requirements. The PV system includes a maximum power tracking inverter and permits feedback of excess PV energy to the utility grid which is connected in parallel with the photovoltaic system. Separate thermal collectors, either liquid or air, provide relatively low temperature energy to either a liquid or rock bed storage unit, which in turn provides solar space heating to supplement the heat pump and preheats domestic hot water. A variation of this system is one in which the solar collectors provide only supplemental energy for domestic hot water heating.

Studied By

- General Electric (Reference #16)
Advantages and Disadvantages

Advantages

• Utility essentially acts as electrical storage medium
• No fossil back-up system required

Disadvantages

• Acceptance of feedback by utility
• Thermal dump required

Conclusions

This system is economically viable in all regions, approaching the performance and cost results of the PV only all-electric/feedback system. Since solar thermal energy is used only for domestic hot water during the summer, small thermal collector areas are required for an optimized economic system. These conclusions are based on a solar thermal to PV collector cost ratio of 2 to 1 (Reference #16). However, as this ratio is reduced to one or lower, optimized solar thermal collector areas increase to 30% or more of the roof area.

System II(b) Direct Solar Heating/Feedback

Block Diagram

Description

This system involves the general household electrical loads and an electrically driven vapor compression space cooling unit. The PV system includes a maximum power tracking inverter and utility feedback capability. Solar thermal collectors, backed-up by a conventional fossil fuel burner, provide space heating and domestic hot water requirements.
Studied By

- General Electric (Reference #16)
- Aerospace (Reference #22)

Advantages and Disadvantages

Similar considerations as listed for the System IIa, Solar Assisted Heat Pump/Feedback. Additional disadvantages are due to need for fossil back-up system.

Conclusions

This system is less economical than separate PV/T systems providing an all-electrical load (IIa), where solar thermal only supplements the heat pump and electrical hot water units. Separate solar systems used for space cooling and heating (i.e., PV for vapor compression cooling, solar thermal for heating) creates seasonal mismatch of collector areas required. As in the case of system IIa, comparatively small thermal collector area required for optimized economic system. However, increased thermal collector areas become more economic as their cost is reduced and fossil fuels escalate in price.

This system is primarily applicable in cold and moderate climate areas, where fossil burners and presently in use and a low to moderate cooling load exists.

System II(c) Solar Rankine Driven HP/Feedback

Block Diagram

![Block Diagram](attachment:image.png)

Description

This system is similar to System Ia, Solar Assisted Heat Pump/Feedback, with the addition of a heat pump that can be driven electrically or with appropriate clutching by a solar driven Rankine engine during the space cooling season. Higher temperature collectors (e.g., vacuum tube) are used to operate the Rankine engine at higher efficiency levels. During the heating season, solar thermal supplements the conventional heat pump operation.
Studied By

- General Electric (Reference #16)

Advantages and Disadvantages

**Advantages**

- Permits use of higher temperature, high efficiency, vacuum tube collectors required for Rankine driven heat pump
- Allows use of thermal energy in summer

**Disadvantages**

- Complexity of Rankine system
- Potentially increased maintenance requirements
- Thermal dump system required

Conclusions

Significant cooling requirements must exist in order to achieve economic viability. The regions designated in this program, have moderate to high summer cooling loads and therefore this system would be applicable. However, maximum return would dictate its application in the warmer regions where both higher insolation and higher cooling requirements exist.

From both the performance and cost standpoint, this system compares favorably with System IIa, Solar Assisted Heat Pump/Feedback.

**System II(d) Solar Absorption Cooling/Feedback**

**Block Diagram**

![Block Diagram](image-url)
Description

In this system, the general household electrical loads are provided by the PV array associated with a maximum power tracking inverter. The system also has feedback capability. Solar thermal collectors, backed-up by a conventional fossil fuel burner, provide space heating, hot water, and space cooling using an absorption chiller.

Studied By

- General Electric (Reference #16)

Advantages and Disadvantages

Advantages

- Permits use of higher temperature, higher efficiency, vacuum tube collectors requires for absorption chiller
- Allows use of thermal energy in summer

Disadvantages

- Higher level of technology over solar heating
- Solar cooling technology currently not as advanced as heating technology

Conclusions

Comments regarding regional applicability of the Solar Rankine Driven Heat Pump/Feedback System, IIc, apply equally well to this system.

The cooling system employing an absorption chiller yields better system performance than one using a Rankine driven heat pump. This is due to the fact that the absorption chiller requires a lower solar temperature than the Rankine system, and thus the collector can operate at higher efficiency. However, from both the performance and economic standpoint, the Rankine driven heat pump system provides somewhat better overall results.

System II(e) Air Solar Boosted Heat Pump/Battery Storage
Description

This system involves all electrically driven loads, with solar thermal energy used to supplement space and hot water heating. A heat pump provides the space heating and cooling requirements. The PV system is the same as that described in connection with System Ia, All Electric System/Battery Storage. Air thermal collectors provide energy to the rock bed storage which in turn serves as a heated air source (i.e., solar boost) for the heat pump during the heating season. The solar thermal system can also provide space heating directly when higher temperatures are available. During the cooling season, the rock bed storage serves as a sink for the heat pump during the daytime hours. The nighttime hours are used to flush out the heat accumulated in storage during the day.

Studies By

- Spectrolab (Reference #20)

Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Rock bed heat source for heat pump improves COP</td>
<td>• Rejects excess collected to atmosphere during cooling season</td>
</tr>
<tr>
<td></td>
<td>• Large rock bed</td>
</tr>
<tr>
<td></td>
<td>• Adequate stratification difficult to achieve</td>
</tr>
</tbody>
</table>
Conclusions

If the rock bed storage is large and sufficiently stratified, this system combines the best features of both the solar boost (also called the series) and solar assisted (also called the parallel or solar supplemented) heat pump systems. However, detailed study (Reference #20) indicated that rock bed size and stratification proved inadequate to achieve the theoretical promise of this system.

System II(f) Solar Assisted Heat Pump/Battery Storage

Block Diagram

Description

Similar to System IIa, All Electric/Solar Assisted Heat Pump, with the use of air thermal collectors and rock bed storage in place of hydronic collectors and water storage system. Battery storage, as in System IIc, is also used in this PV system instead of utility feedback.

Studied By

- Spectrolab (Reference #20)

Advantages and Disadvantages

Advantages

- Lower thermal operating temperature
- Possible lower equipment costs

Disadvantages

- Large rock bed storage
- DHW only summer demand
Conclusions

This system is economically attractive in all regions, with increased viability in regions where heating loads exceed cooling loads. Use of utility feedback in place of battery storage would further enhance performance and economic viability of this system.

Since solar thermal used only for domestic hot water during the summer, small thermal collector areas required for optimized economic system, particularly in warmer climate regions.

System II(g) Solar Boosted Heat Pump/Feedback

Block Diagram

Description

This system involves all electric loads, with space heating and cooling provided by a heat pump. The PV system includes a maximum power tracking inverter and utility feedback capability. The hydronic solar thermal system can operate in either of two modes (i.e., dual modes), (1) as a water source for the heat pump or (2) provide direct solar space heating. In addition, the solar thermal system supplements the electrical resistance heated domestic hot water supply. In the cooling mode, a wet cooling tower and cold thermal energy storage are used to increase the overall efficiency of the heat pump. Heat is rejected from the heat pump condenser to the ambient air through the cooling tower. Cold water storage permits shifting operation of the compressor to periods when either solar photovoltaic power is available or inexpensive off-peak utility power can be purchased at lower rates.
Winter operation involves the use of electric resistance heating when thermal energy storage tank temperature is below 45°F; thermal storage acts as a source for the heat pump between 45°F and 80°F, and direct solar is fed to the air handling duct when thermal storage temperature is above 80°F. For summer cooling, the cold water storage tank temperature is maintained between 40°F and 60°F. If photovoltaic power is available to run the compressor and tank temperature is above 40°F, the heat pump will be operated to remove heat from the tank. If tank temperature goes above 60°F, the compressor is operated independently of the availability of photovoltaic power. When tank temperature goes below 40°F, any photovoltaic power available is fed to the utility.

A variation of this system uses a dual mode heat pump, capable of utilizing either ambient air or solar heated water as a source. When thermal storage drops below a minimum temperature level, the heat pump switches to ambient air source if outside temperature level is high enough to provide COP greater than 1, rather than switching to auxiliary resistance heating at a COP of 1.

Studied By

- MIT-Lincoln Laboratory and University of Texas at Arlington
  (Reference #12 and #24)

Advantages and Disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Higher COP for heat pump</td>
<td>• Cooling tower to reject heat from heat pump condenser in cooling mode</td>
</tr>
<tr>
<td>• Cold thermal storage permits operation of heat pump to store PV power</td>
<td>• Cold water storage tank</td>
</tr>
<tr>
<td></td>
<td>• In solar direct heating mode, needs larger than normal heat transfer surface area</td>
</tr>
<tr>
<td></td>
<td>• In heating mode, when collector or storage inadequate, heat pump must shut-off, requiring auxiliary electric resistance heating (COP=1)</td>
</tr>
</tbody>
</table>

Conclusions

This system is under test at the University of Texas at Arlington Solar Energy Research Facility as part of MIT-Lincoln Laboratories "Solar Hybrid Energy Project."
This system is primarily applicable in areas where both substantial heating and cooling loads exist. To take maximum advantage of the solar boost mode, the area should experience a significant amount of days in which the temperature drops below the 20°F mark.

**Comparison Evaluation of PV Only Systems**

A comparative evaluation of each of the separate PV/Thermal systems against a set of criteria previously described in Section 2.0 is presented in Table A-2. The evaluation resulted in the following ranking of separate PV/Thermal systems.

<table>
<thead>
<tr>
<th>Rank</th>
<th>System Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IIa, All Electric/Solar Assisted Heat Pump/Feedback</td>
</tr>
<tr>
<td>2</td>
<td>IIb, Solar Absorption Cooling/Feedback</td>
</tr>
<tr>
<td>3</td>
<td>IIc, Solar Rankine Driven Heat Pump/Feedback</td>
</tr>
<tr>
<td>4</td>
<td>IId, Direct Solar Heating/Feedback</td>
</tr>
<tr>
<td>5</td>
<td>IIe, Air Solar Assisted Heat Pump/Battery Storage</td>
</tr>
<tr>
<td>6</td>
<td>IIf, Solar Boosted Heat Pump/Feedback</td>
</tr>
<tr>
<td>7</td>
<td>IIg, Air Solar Boosted Heat Pump/Battery</td>
</tr>
<tr>
<td>SELECTION CRITERION</td>
<td>SYSTEM I(a)</td>
</tr>
<tr>
<td>---------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>RESULTS</td>
<td>GOOD</td>
</tr>
<tr>
<td>CURRENT TECHNOLOGY</td>
<td>GOOD</td>
</tr>
<tr>
<td>STATUS</td>
<td>GOOD</td>
</tr>
<tr>
<td>DEVELOPMENT RISK</td>
<td>GOOD</td>
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</table>

ECONOMIC PERFORMANCE

<table>
<thead>
<tr>
<th>MINIMUM SIMPLIFICATION OF SYSTEM COMPONENTS</th>
<th>RANKING</th>
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</thead>
<tbody>
<tr>
<td>GOOD</td>
<td>1</td>
</tr>
<tr>
<td>GOOD</td>
<td>2</td>
</tr>
<tr>
<td>FAIR</td>
<td>3</td>
</tr>
<tr>
<td>POOR</td>
<td>4</td>
</tr>
<tr>
<td>FAIR</td>
<td>5</td>
</tr>
<tr>
<td>FAIR</td>
<td>6</td>
</tr>
<tr>
<td>GOOD</td>
<td>7</td>
</tr>
</tbody>
</table>

TABLE A-2. COMPARISON EVALUATIONS OF SIDE-BY-SIDE SYSTEMS
COMBINED PV/ THERMAL SYSTEMS

System III(a) Solar Assisted Heat Pump/Feedback

Block Diagram

Description

This is the same system as IIa, with combined PV/Thermal collectors replacing separate collectors. A variation of this system involves elimination of the maximum power tracker and utility feedback capability; instead, using battery storage, a shunt regulator and battery charge controller.

Studied By

- General Electric (Reference 16)
- Westinghouse (References 18 and 19)
- Spectrolab (Reference 20)
- MIT-Lincoln Laboratory (Reference 13)
Advantages and Disadvantages

Advantages

• Potentially lower cost collectors than equivalent separate collectors
• Lower installation costs
• Lower roof space requirements

Disadvantages

• Combined collector degrades performance of both PV and thermal
• Limits flexibility between PV and thermal collector area required for the various regions being considered
• DHW only thermal load in summer
• No acceptable combined collector design presently available

Conclusions

This system is most applicable in regions with high heating; however, these regions usually have relatively lower annual insolation. The lower insolation levels coupled with degraded performance associated with combined PV/Thermal collectors necessitates large collector areas to satisfy a reasonable solar thermal contribution. During the summer months, collector thermal output is used only to provide domestic hot water with resultant waste of excess solar thermal energy.

Though less viable than PV only or separate collector systems, this system, serving the all-electric load with a solar assisted heat pump, is more cost effective than the combined collector, direct solar heating/battery storage system (IIIb) which uses a fossil fuel burner for thermal back-up, or the solar boosted heat pump system (IIIc).

System III(b) Direct Solar Heating/Beedback

Block Diagram
Description

This is the same system as IIb, with combined PV/Thermal collectors replacing separate collectors. A variation of this system involves elimination of the maximum power tracker and utility feedback capability; instead, using battery storage, a shunt regulator and battery charge controller.

Studied By

- General Electric (Reference 16)
- Westinghouse (Reference 18)
- MIT-Lincoln Laboratory (Reference 13)

Advantages and Disadvantages

Same as System IIIa, Solar Assisted Heat Pump/Feedback. Additional disadvantage due to need for fossil back-up system.

Conclusions

This system is considerably less effective than System IIIa, Solar Assisted Heat Pump in most locations - except for cold areas, where thermal demands are high. As pointed out in the conclusions associated with System IIIa, combined collectors are not as effective as the other collector options reviewed in this report. Therefore, this system would seem to offer less promise in the future than System IIIa.

System III(c) Solar Boosted HP/Feedback

Block Diagram
Description

Again this system is the same as System IIg, with combined PV/Thermal collectors replacing separate collectors and without a cold water storage tank. A variation of this system involves elimination of maximum power tracker and utility feedback capability; instead, using battery storage, a shunt regulator and battery charge controller.

An additional variation of this system uses a dual mode heat pump, capable of utilizing either ambient air or solar heated water as a source. When thermal storage drops below a minimum temperature level, heat pump switches to ambient air source if outside temperature is high enough to provide COP greater than 1, rather than switching to auxiliary resistance heating at a COP of 1.

Studied By

- Spectrolab (Reference 20)
- Westinghouse (Reference 18)
- MIT-Lincoln Laboratory (Reference 13)

Advantages and Disadvantages

Advantages

- Water source improves COP of heat pump

Disadvantages

- In heating mode when collector or storage inadequate, heat pump must shut-off, requiring auxiliary electric resistance heating (COP=1)
- Cooling tower to reject heat from heat pump condenser in cooling mode
- In solar direct heating mode, needs larger than normal heat transfer surface

Conclusions

This system is not as effective as the combined collector solar assisted heat pump, system IIIa, from both the performance and economic standpoint. This system is primarily applicable in areas where both substantial heating and cooling loads exist, and optimum array sizes are comparatively large. When small collector areas are used, insufficient stored thermal energy is available to the heat pump evaporator to allow full-time solar boost operation. Under this condition, the space heating load is met by electric resistance heating at a COP of 1. The large size thermal energy storage established as optional to reduce auxiliary resistance heating adds substantially to the cost of the solar boost system.
This system is also considerably more complex and has a higher initial cost than either combined PV/Thermal Systems IIIa or IIIb.

**System III(d) Direct Heating/Battery Storage/Stand Alone**

**Block Diagram**

This is a completely autonomous system with no connection to the utility grid. Combined PV/Thermal collectors are used in conjunction with electrical and thermal storage. Back-up is handled by a small auxiliary diesel electric generator (on the order of 1.5 KW) and a fossil fuel burner. Loads are all-electric with the exception of space heating. The PV array (or battery storage) provides electrical energy to the general household loads, a vapor compression cooling unit, and the domestic hot water heater. Thermal energy generated in the combined array (or by the fossil burner) provides direct space heating and supplemental hot water heating.

Both the electrical and thermal storage are essential to a stand-alone system. During the day, energy derived from the solar system is stored to get through the night. If storage energy is inadequate, the auxiliary supply either provides energy directly or increases the energy store. This allows the auxiliary systems to be of low capacity. Thus, the storage systems not only provide storage, but handle peak loads.
The solar system should be capable of providing on the order of 80% to 90% of the household electrical and thermal loads. The auxiliary electrical generator should run no more than 1000 hours per year and fossil fuel uses approximately 10% for electrical back-up and 20% for thermal back-up.

In addition to the combined PV/Thermal collectors depicted in the above schematic, variations of the system involve the use of PV only collectors, and PV only side by side with combined collectors sized appropriately for the specific locations.

Another variation of the stand-alone system involves the all-electric residence, pv only array, and heat pump for providing space heating and cooling. Energy for hot water is partially supplied by excess PV electrical energy in spring and fall and by reject heat from the air conditioning in the summer.

Waste heat from the diesel generator represents another potential source of thermal energy that could be applied in satisfying residential demand.

Studied By

- Westinghouse (References 18 and 19)

Advantages and Disadvantages

**Advantages**

- No utility interface
- Potential for lower energy cost

**Disadvantages**

- Potential noise and environmental problems
- Must assure continuous internal energy availability
- Residence designed to minimize exceptional loads
- Load management unit may be necessary to minimize extremes due to the system's limited peak power
- Extensive amount of equipment and maintenance
Conclusions

Stand-alone systems are viable virtually everywhere that utility back-up systems are viable. Stand-alone systems favor combined PV/Thermal collectors in cold regions. Large collector array areas are required to meet 90% of total annual load requirements in colder/lower insolation areas, such as Cleveland. In regions with moderate heating requirements, the collector area required for optimum electrical input can readily exceed the optimum combined collector area needed for direct thermal conversion. Since combined collectors are more costly, a combination of PV only and combined collectors are more appropriate for these regions. In very warm areas, where air conditioning loads predominate, PV only collectors meet requirements.

Comparison Evaluation of Combined PV/Thermal Systems

A comparative evaluation of each of the combined PV/Thermal systems against a set of criteria previously described in Section 2.0 is presented in Table A-3. This evaluation resulted in the following ranking of combined PV/Thermal systems.

<table>
<thead>
<tr>
<th>Rank</th>
<th>System Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IIIa, Solar Assisted Heat Pump/Feedback</td>
</tr>
<tr>
<td>2</td>
<td>IIIb, Direct Solar Heating/Feedback</td>
</tr>
<tr>
<td>3</td>
<td>IIIId, Stand-Alone/Direct Heating/Battery</td>
</tr>
<tr>
<td>4</td>
<td>IIIIc, Solar Boosted Heat Pump/Feedback</td>
</tr>
<tr>
<td>Selection Criteria</td>
<td>System III (a)</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Economic/Performance Results</td>
<td>FAIR</td>
</tr>
<tr>
<td>Current Technology Status</td>
<td>FAIR</td>
</tr>
<tr>
<td>Projected Status for 1986</td>
<td>FAIR</td>
</tr>
<tr>
<td>Development Risk</td>
<td>GOOD</td>
</tr>
<tr>
<td>System Complexity</td>
<td>FAIR</td>
</tr>
<tr>
<td>Projected System Cost</td>
<td>FAIR</td>
</tr>
<tr>
<td>Region Applicability</td>
<td>FAIR</td>
</tr>
<tr>
<td>Minimum Duplication of System Components</td>
<td>GOOD</td>
</tr>
</tbody>
</table>

RANKING

1  2  3