The Design of a Photovoltaic System for a Passive Design Northeast All-Electric Residence

E. M. Mehalick, G. F. Tully, J. Johnson, J. Parker, R. Felice
Philadelphia, PA 19101

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THE DESIGN OF A PHOTOVOLTAIC SYSTEM
FOR A PASSIVE DESIGN NORTHEAST ALL-ELECTRIC RESIDENCE

E. M. Mehalick, G. F. Tully,
J. Johnson, J. Parker, R. Felice
General Electric Energy Systems and Technology Division
General Electric
Advanced Energy Programs Department
P. O. Box 8555
Philadelphia, Penn. 19101

ABSTRACT

A photovoltaic system has been developed and integrated into a passively designed, low energy consuming home suitable for the Northeast region of the country. The selected array size is 4.1 kW at NOCT conditions, and covers 51 sq.m. of roof area. The design addresses the residential market segment of low energy consuming houses with limited roof area availability for photovoltaic arrays. A direct mount, next generation, larger sized, PV shingle module is used to reduce installation costs over earlier generation shingle modules. A 4 kW line-commutated inverter is used in the power conversion subsystem, since it is representative of currently available equipment. This report describes the complete system and house design, including all the pertinent installation and construction drawings. Specific performance results are presented for the Boston and Madison region. The system design presented in the report, coupled with previously completed designs, provide a set of design options expected to be available to residential homeowners in the mid 1980's.

FOREWARD

This report presents the fourth of six detailed residential designs developed on the Detailed Residential Photovoltaic System Preferred Designs Study. The Advanced Energy Programs Department of the General Electric Company, Energy Systems and Technology Division, performed the contract 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 choice of hardware for this design is made primarily based on available data within the time constraints of this effort and should not be considered an endorsement of the hardware. The set of designs consider the implementation of various hardware components, including different flat PV modules, selected roof mounting techniques and various power conditioning equipment. The complete set of system designs, therefore, provide detailed design information on several manufacturers' hardware options.

The intent of the detailed design is to provide sufficient detail for obtaining a system installation cost estimate. A design package for this installation can be formulated using the two appendices (Appendix A, Power Conversion Subsystem Specification; and Appendix B, Electrical Installation Specifications), along with a drawings package (architectural drawings AI-All and electrical drawings E1-E9). These drawings are included as foldouts within the report text and a full size set is delivered to Sandia.

The system design development and preparation of this report was supported by contributions of the following individuals: Mr. G. Tully, of Massdesign Architects and Planners, Inc., for the residential house design, and photovoltaic array installation details; Mr. G. W. Johnson, of Johnson and
Stover, Inc., for the electrical system installation specification; General Electric employees including Mr. R. Felice for overall system design and Mr. J. Parker for system performance analysis.
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<td>F-1</td>
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SECTION 1
BACKGROUND

Application Description

The photovoltaic (PV) system design described in this report is for a residential two-story, passively heated house located in the Northeast region of the country typified by the Boston/Madison weather environment. The house design presents a minimum of south facing roof typical of this style. The house is assumed newly constructed in 1986 with a living floor area of 157 sq.m. (1690 sq.ft.) and a rectangular south facing roof area of 57 sq.m. (614 sq.ft.). A perspective of the house is shown in Figure 1-1. The design includes energy conservation features projected for 1986 and additional passive design features such as a greenhouse. An advanced performance 2 1/2 ton heat pump is used for heating and cooling with an electric hot water heater. The garage is separate from the house. The equipment area is located in the basement area.

The electrical energy derived from the PV system serves the normal household electrical requirements including general appliances, lighting, cooking, hot water heating and heat pump operation. When PV generated energy exceeds the house requirements, excess energy is directed back to the utility grid.

Design Criteria

The objective of the program is to develop designs of residential photovoltaic systems which can be used as reference designs estimates. The level of detail is sufficient to allow independent cost estimates for installation of the system. Specifications for equipment are based on currently
Figure 1-1. Perspective of a Northeast Passive House
available components or similar currently available equipment if the component is not available at present.

In general, the homeowner is considered the system user; therefore, operation and maintenance requirements typical of conventional HVAC systems are assumed. The system excludes instrumentation, since a mature system installation is assumed.

To evaluate the performance of the system design, typical hourly electrical load profiles and space conditioning demands for the house are used. These load profiles were developed in the GE Regional Residential Study, Reference 1, and updated in the Residential Load Center Program, Reference 2. All the system performance analyses are 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, are used for system sizing and tradeoffs.

Previous designs, References 4, 15 and 16, have dealt with applications having higher diversified electrical loads and higher space conditioning loads. The system designs had array areas ranging from 74 sq.m. to 93 sq.m. Therefore, the design criteria used for this design requires a highly passive house design, reducing thermal load requirements by approximately 50% and improved efficiency appliances with an energy conscious family. The total electrical load reduction is approximately 14% over the previous Northeast residence designs. Consistent with the reduced loads is a house design having a smaller south facing roof area. The smaller roof area requirement provides more flexibility to the architectural features of the house.

Furthermore, the Southwest design presented in Reference 4 used a
hexagonal shaped module with 0.196 sq.m. exposed module area. This small module size may imply high installation costs. Therefore, the design considers a larger shingle module (.916 sq.m. exposed module area) for comparison to the previous design.

Project Team

The project team for the design effort consists of the participants listed in Figure 1-2. General Electric Company, Advanced Energy Programs Department, is the prime contractor with responsibility for system design and integration and project management. Massdesign Architects and Planners, Inc., provides the details of the house design and analysis support related to the solar array installation. Johnson and Stover, Inc., provides the installation drawings for the electrical equipment associated with the photovoltaic system.

Figure 1-2 Project Team
Report Format

The design details are presented in the main section of the report and all background data and material in the Appendices. Section 2 is a concise summary section presenting the design in bullet form. The next three sections present all of the design details. Section 3 covers the system description. Section 4 discusses the residential house design, and Section 5 provides the subsystem specifications. The latter section includes most of the electrical installation drawings and details and discusses the two primary subsystems, the array and the power conversion subsystem (PCS).

Finally, the Appendices provide design details such as the PCS specification and electrical system installation specification. Background material on the cost assumptions and input data, several backup design tradeoffs, and parametric variations are also discussed.
SECTION 2

SUMMARY

This section presents a brief overview of the key system design elements and a synopsis of key design tradeoffs. Subsequent sections of the report discuss the details of each of the topic areas.

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 is used for system sizing. The analysis considers various array sizes and provides parametric performance results. In general, under the assumed economic assumptions and with utility sellback rates of 50% or greater, the results indicate a PV array size as large as the available roof area. This design addresses the requirements of a low energy consuming house with a minimum of available roof area, and provides installation details on a direct mounted shingle module significantly larger than earlier designs.
House Description

- 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 and ENERGY CONSERVATION FEATURES projected in 1986.
- There is 157 sq.m. (1690 sq.ft.) of living area with a 9 sq.m. (96 sq.ft.) greenhouse and 57 sq.m. (614 sq.ft.) 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 51 sq.m. 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 of 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 180 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 51 sq.m. of roof area.

- The array orientation is due south with a roof pitch of 33.7 degrees. The overall cell packing efficiency is 95% over the 51 sq.m.

- 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 Flat Conductor Cables (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 95 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 48 cells is also used in the installation.
- For a NOCT of 65 degrees C, the MAXIMUM POWER OUTPUT is 74W and 16.6V at SOC conditions (1 kW/sq.m., 20 degrees 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 sq.m.</td>
<td>0.433 sq.m.</td>
</tr>
<tr>
<td>- Exposed Module area</td>
<td>0.916 sq.m.</td>
<td>0.458 sq.m.</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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power Rating</td>
<td>4.0 kW Continuous</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>240 Vac Utility Residential Service</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>168 ±12 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 degrees C</td>
</tr>
</tbody>
</table>
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 acts as a conventional utility service; therefore, its entrance to the residence is parallel to the utility line.

- An external switch provides a means to externally disconnect the array and the PCS equipment.

- An equipment area is located in the southwest corner of the basement level.
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.

![Graphs showing life cycle cost ratio vs collector area for Boston and Madison with sell back ratio notes and price of electricity information.](image-url)
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.

![Graphs showing energy output for Boston and Madison](Image)

<table>
<thead>
<tr>
<th>Location</th>
<th>Utility Make-Up</th>
<th>% of Load Supplied Directly</th>
<th>Insolation on Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boston</td>
<td>10.6 MWh</td>
<td>25.3</td>
<td>1338 KWH/m²</td>
</tr>
<tr>
<td>Madison</td>
<td>11.6 MWh</td>
<td>25.3</td>
<td>1456 KWH/m²</td>
</tr>
</tbody>
</table>
SECTION 3
SYSTEM DESCRIPTION

Functional Description

System

The grid connected residential PV system for the Northeast provides the space conditioning requirements and all conventional electrical load requirements for an all electric home. The system consists of two major subsystems: The PV solar array and the power conversion subsystems. Figure 3-1 shows a system block diagram. The 51 sq.m. solar array uses a rectangular shingle solar cell module being developed by General Electric. The module is selected as a next generation to the Block IV module currently available. The array is wired in a redundant series/parallel matrix with a 4.1 kW rated peak output. The array size is based on the results of marginal life cycle cost analysis consistent with the available roof area for a passively designed house. The photovoltaic generated power is supplied to a 4 kVA PCS which is controlled to track the solar array maximum power operating point. A line-commutated Gemini unit is selected based on its current availability. The PCS feeds 240 Vac power directly to the house loads or back to the utility when excess power is generated. The PV power is isolated from the utility by a 5 kVA transformer.

The overall system connects in parallel with the utility service to supply the residential load. Power generated by the array in excess of residential loads is fed back into the utility grid. With this arrangement, all house load demands are met, no electrical storage is required, and all net energy output of the photovoltaic system is used.
Varistors located at the positive dc line terminal and the ac service panelboard provide protection from lightning-induced voltage transients. These varistors protect the input and output PCS circuitry from induced high voltage surges. The remainder of the electrical equipment consists of disconnects and fused circuit breakers to isolate all the subsystems from each other and provide an exterior disconnect switch to meet the code requirements for self-generating power sources.

System operation is described 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 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 180 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.

The system represents the simplest photovoltaic design with a minimum of components and controls. A key to the implementation of this design is the acceptance of the feedback energy by the utility and the price the utility will pay to the homeowner for this energy.

Components

A one line diagram of the system components is shown in Figure 3-2. This section briefly describes the major functional elements of the system with further details contained in Section 5.

**Solar Array** -- The solar array consists of 52 full and 8 half shingle modules connected electrically in a redundant series/parallel circuit arrangement. Eight modules are connected in series and with 7 parallel circuits. The module electrical circuit terminates in positive and negative busbars which are connected to cabling and run in conduit to the equipment room. The negative busbar is grounded. The array output is 4.1 kW at NOCT conditions.

**PCS** -- The PCS provides the electrical interface between the solar array and the residential ac service. This subsystem consists of a dc input filter, dc/ac inverter, a transformer and maximum power tracker and control circuits. This subsystem inverts the variable dc output of the solar array to supply ac residential service in parallel with the utility electrical service.

**Inverter** -- The inverter is a Silicon Control Rectifier (SCR) thyristor bridge circuit providing unidirectional current flow on the input dc side and alternating current flow on the output ac side. It is sized at 4 kVA and is line commutated.
Figure 3-2 Residential Photovoltaic One Line Diagram
Transformer -- The 5 kVA transformer isolates the ac and dc circuits and matches the output dc voltage of the array to the normal ac line voltage.

DC Filter -- This filter smooths the dc current flow which is subject to high harmonics as a result of the switching action of the thyristors.

Inverter Controls -- These controls provide the timing signals for firing of the thyristors and, in turn, control the level and direction of power flow through the power conversion subsystem.

Maximum Power Control -- This control circuit modifies the inverter timing control circuit to operate the array at its dynamic maximum power point.

RFI Filter -- This filter attenuates high frequency output harmonics to minimize radio and TV interference.

Exterior Array Fused Breaker -- This breaker provides a visible exterior disconnect and is fused only if required by a strict National Electric Code interpretation.

Varistors -- These devices provide lightning protection. They are connected to the dc and ac residence input lines and provide induced transient protection of the input and output PCS circuitry.

Interior Disconnects and Breakers -- An interior dc disconnect and a service panelboard circuit breaker provide isolation of the PCS for installation and service. The service panelboard circuit breaker also isolates the utility service from the solar array system.
System Design Requirements

A review of the environmental conditions applicable to the Northeast region of the country, the goals for the implementation of residential PV systems in 1986, and the specific constraints associated with residential house designs have lead to the broad system design requirements listed in Table 3-1. The environmental conditions listed are typical of the Northeast region. The region has a moderate lightning environment which imposes only nominal requirements on the design. The risk of hailstone damage in the Northeast is also relatively moderate. The tempered glass cover of the rectangular shingle module is the same as the Block IV Module which has passed hailstones tests conducted by JPL.

The table also lists the average daily load requirements for the two regions. The heat pump average load requirements are based on the annual electrical input to the heat pump required to satisfy both the space heating and cooling requirements. Since no specific site is considered for the installation, no specific local building, fire or electrical codes are imposed. The design considers the general Model Code requirements appropriate for the Northeast. The overall electrical design tries to assure safety in the normal residential application.

The house is a new construction; therefore, the site constraints do not impose any significant design requirements. The house orientation is due south and the south facing roof slopes at 33.7 degrees (8 to 12 pitch). The roof slope is consistent with standard framing member sizes. The roof area covers 57 sq.m. and it is consistent with the aesthetic features of the house design. No landscape shadowing or surrounding building shadowing is allowed.
System operating constraints require utility grid connection with the PV system operating in parallel and synchronized with the utility. If utility interruption occurs, the PV system disconnects.
Table 3-1

System Design Requirements

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
<th>Boston</th>
<th>Madison</th>
</tr>
</thead>
<tbody>
<tr>
<td>-- Ambient temperature:</td>
<td>-20 to 39°C</td>
<td>-34.4 to 36.7°C</td>
</tr>
<tr>
<td>-- Module Thermal Cycle Test:</td>
<td>- - - -40 to 90°C - - -</td>
<td></td>
</tr>
<tr>
<td>-- Wind:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremes</td>
<td>27 m/s</td>
<td>34.4 m/s</td>
</tr>
<tr>
<td>-- Moderate Lightning Area:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Isokeraunic Level</td>
<td>20</td>
<td>41</td>
</tr>
<tr>
<td>-- Hail:</td>
<td>- - - Low - - -</td>
<td></td>
</tr>
<tr>
<td>-- Annual Horizontal Insolation:</td>
<td>1341 kWh/m²</td>
<td>1472 kWh/m²</td>
</tr>
</tbody>
</table>

Application Requirements

- Electrical Load Summary:
  - Average Daily Base Electrical Load 18.4 kWh/day 18.4 kWh/day
  - Average Daily Hot Water Load 13.0 kWh/day 13.4 kWh/day
  - Average Daily Heat Pump Load 7.7 kWh/day 11.0 kWh/day
  - Annual Electrical Load 14272 kWh 15622 kWh

- Load: Single Phase 240/120 Vac
- Life: 20 Year Design Life
- Meet Local Building and Electrical Codes
- Meet Local Fire District Regulations

Site Constraints (General Considerations)
- Roof Area Available
- Roof Slope
- House Orientation
- Sun Rights

System Operational Constraints
- Disconnect Photovoltaic System if Utility is Interrupted
- Operate in Parallel and Synchronized with the Utility
Performance Characteristics

The estimated residential photovoltaic system performance for Boston is summarized in Table 3-2. The solar array consists of 56 rectangular shingle modules in an 8 series by 7 parallel matrix. Each module has 96 9.5 cm square cells, or .866 sq.m. of cell area per module. The module has a cell packing efficiency of 0.945. The total nominal solar cell area is 48.5 sq.m. The exposed glass coverplate area of the shingles on the roof covers 51.3 sq.m. The roof is 11.2 m. wide by 5.11 m. high, resulting in a total roof area of 57.1 sq.m. Thus, the overall roof packing efficiency of cells on the roof is 85%.

The calculated rated output of the solar array at Standard Operation Conditions (including an NOCT of 65 degrees C) is 4.1 kW. On an annual basis, the ac energy output for Boston is 5638 kWh with a total insolation of 1338 kWh/sq.m. on the 33.7 degree sloped roof. Thus, the overall system conversion efficiency is 8.2%. For Madison, the corresponding system efficiency is 8.3% with 6310 kWh of ac energy output for an incident insolation level of 1486 kWh/sq.m. For both locations, the solar array conversion efficiency varies between 9.3% in Boston to 9.5% in Madison, with less than 1% annual energy loss due to the series resistance losses in the shingle module bus strips, the termination busbars, and the cabling between the busbars and the inverter. The estimated annual PCS efficiency is approximately 89.2% (89.9% in Boston and 88.4% in Madison) resulting in the overall system efficiencies noted. The system output for each location is greater than 50% of the diversified electrical baseload.
### Table 3-2
Summary of System Performance

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Modules (8 series x 7 parallel)</td>
<td>56</td>
</tr>
<tr>
<td>Total Solar Cell Area ($m^2$)</td>
<td>48.5</td>
</tr>
<tr>
<td>Total Exposed Module Area ($m^2$)</td>
<td>51.3</td>
</tr>
<tr>
<td>Module Packing Factor</td>
<td>0.95</td>
</tr>
<tr>
<td>Total Gross Roof Area ($m^2$)</td>
<td>57.1</td>
</tr>
<tr>
<td>Array Output at SOC NOCT = 65°C (kW Peak)</td>
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<tr>
<th></th>
<th>BOSTON</th>
<th>MADISON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual dc Energy Input to Inverter (kWh)</td>
<td>6272</td>
<td>7131</td>
</tr>
<tr>
<td>Annual ac Electrical Energy Output (kWh)</td>
<td>5638</td>
<td>6310</td>
</tr>
<tr>
<td>Annual Insolation on Array Surface (kWh/m$^2$)</td>
<td>1338</td>
<td>1486</td>
</tr>
</tbody>
</table>

**Overall System Efficiency** = $\frac{\text{System Output}}{\text{Insolation} \times \text{Array Area}}$

- BOSTON: 8.2%
- MADISON: 8.3%

**Array Conversion Eff.** = $\frac{\text{dc Energy to Inverter}}{\text{Insolation} \times \text{Array Area}}$

- BOSTON: 9.3%
- MADISON: 9.5%
The I-V characteristics of the array at reference conditions are summarized on Figure 3-3. The NOCT array output is 4.1 kWp at 132V and 31.2A.

Figure 3-3 Solar Array I-V Characteristics at NOCT Conditions

Design Tradeoffs

System performance and economic analyses provide the basis for selecting the collector array size for both the Boston and Madison regions. In addition, the roof slope is selected based on sensitivity studies to maximize output. The models and input data used for all of these analyses are discussed in Appendix D. The loads used in the analyses are reduced from previous Northeast designs. The largest reduction occurs in the space conditioning loads, which are reduced by 48%. The overall electrical load reduction is 14%.

Array Tilt Sensitivity

The sensitivity of collector tilt or roof slope angle to net system is
shown in Figure 3-4. The results indicate that the system output is maximized at a roof slope of 34 degrees, or approximately 10 degrees less than the latitude. The result is consistent with results for optimum array tilt angle from previous studies. The actual design slope selected is 33.7 degrees, which conforms to the use of standard framing techniques (8 to 12 pitch). The figure shows that only small differences in net system output occur over the tilt angle range of 20 degrees to 40 degrees.

![Figure 3-4 Array Tilt Angle Sensitivity in Boston](image)

**Collector Array Sizing**

Array sizing is evaluated for both the Boston and Madison regions. The array area is varied from 21 sq.m. to 64 sq.m. by maintaining 8 series modules along the roof slant height, yielding the same system operating voltage, and adding parallel circuits. The system performance as a function of array area is shown in Figure 3-5 for each location. The performance is defined in terms of total energy output and the energy delivered directly to the load. The effect of array area on system performance in Boston and Madison is quite similar. Over the range of area variation considered, the total system output increases in
direct proportion to array area; whereas, the amount of energy delivered directly to the load approaches a limit dictated by the magnitude and shape of the load profile during daylight hours. Since the PV system output is proportional to array size, and the size of the array impacts the system cost, the effect of array size is best evaluated by means of economic parameters such as life cycle cost ratio (LCCR). The expression for LCCR in terms of levelized annual costs is:

\[
\text{LCCR} = \frac{\text{LEVELIZED COST OF PV SYSTEM} + \text{LEVELIZED COST OF BACKUP ENERGY}}{\text{LEVELIZED COST OF CONVENTIONAL ENERGY}}
\]

The LCCR ratio can also be written in terms of the levelized annual costs (LAC) and levelized annual benefits (LAB) as

\[
\text{LCCR} = \frac{\text{LAC}_{\text{solar}} + (\text{LAC}_{\text{conv}} - \text{LAB})}{\text{LAC}_{\text{conv}}}
\]

LAC\text{\textsubscript{solar}} represents the levelized annual costs of the total solar system and LAC\text{\textsubscript{conv}} represents the levelized annual costs of the conventional energy for the all-electric house in this application. The minimum LCCR value represents the optimized economic PV system size for the application. Photovoltaic systems and energy systems typically follow the law of diminishing returns, that is, each additional unit of size or capacity contributes less benefit than the preceding unit. Whenever an additional unit, for example a square meter of PV array, can show levelized annual savings greater than levelized annual costs, the unit can be economically added. The minimum LCCR value represents the point where the marginal costs equal the marginal benefits. Appendix E describes the calculation of the economic terms and lists all economic assumptions and cost estimates.

3-13
Figure 3-5 Performance as a Function of Array Area in Boston and Madison
The LCCR is calculated for each system for three different utility sellback energy ratios. Figure 3-6 shows these results which reflects the regional differences of the cost of electricity and the weather between Boston and Madison. For example, in Boston the PV system is economically viable (LCCR<1) for array areas greater than 27 sq.m. for sellback ratios of 0.3 or greater; whereas in Madison, sellback ratios of 0.7 or greater are required for economic viability. These results assume an energy price escalation rate of 4% above inflation.

The array area associated with the minimum LCCR also varies directly with sellback ratio. For a sellback ratio of 0.3 in Boston, the area at minimum LCCR is about 59 sq.m. At sellback ratios of 0.5 or greater, the area at minimum LCCR is greater than 64 sq.m. Since the residence has an available roof area of 57.1 sq.m., the largest rectangular shingle array configuration that the roof can accommodate consists of 8 series by 7 parallel circuits covering 51.3 sq.m.

In Madison, the PV system is economically viable for array areas greater than 60 sq.m. at a sellback ratio of 0.7. For smaller areas and lower sellback ratios, the systems are not economical for the given set of costs, energy prices and economic scenario assumed. Since the largest array which can fit on the roof is 51.3 sq.m., a utility sellback ratio greater than 0.7 is implied for economic viability. The assumed price of energy in each location is the major factor contributing to the difference in economic conclusions between Boston and Madison. In Boston, the assumed price of electricity is $0.0832/kWp (1980$); whereas in Madison, the assumed price is $0.532/kWp (Reference 3). The selected system size demonstrates the economic viability of smaller-sized systems for passively designed houses in the Northeast.
Figure 3-6 Life Cycle Cost Ratio as a Function of Collector Area for Boston and Madison

Notes:
1. Price of Electricity
   - Boston: $0.0832/KWH
   - Madison: $0.0532/KWH
Load Sensitivity

The system performance evaluations are based on average residential loads described in Appendix D. Variations in electrical loads from these average values can exist, reflecting a range of energy conservation practices within the home. The effects on the system by the change in loads is evaluated for Boston. The space conditioning loads are not varied, since the design of the houses represent tight, well-insulated construction with thermostats set at relatively low settings. It is also noted that only the load levels are varied, while the load profile remains unchanged.

The results of this load variation on annual energy cost are shown in Figure 3-7. The upper curve represents the levelized annual energy cost as a function of electrical load for the residence without any PV system. The lower curves define the levelized annual energy cost as a function of electrical load and sellback ratio for the same residence incorporating the PV system. The difference between the energy cost without a PV system and the energy cost with a PV system represents the total energy savings associated with the PV system. For sellback ratios less than unity, the savings accrued with the PV system increase with increasing load. This is a direct result of the distribution of the PV energy used directly in the house and that portion sold back to the utility since the net system output is the same for all the cases. As the load increases, more PV energy can be directed to the load and less is sold back. The energy used directly provides a greater benefit than if it were sold to the utility at a reduced rate. As the load is reduced, the reverse is true -- less PV energy is used directly in the house and more is sold back with the result that savings are reduced. It is also noted in the figure that as the sellback
As the price increases, the effect of load level on the savings is diminished. For a sellback ratio of unity, the energy cost savings associated with the PV system are independent of load, since the value of the energy sold back to the utility is equal to that purchased from the utility.

For the present analysis, with the nominal design load profile, 36% of the system output exceeds the house load demand and is sold back to the utility. When the actual load is reduced to 50% of nominal, 57% of the system output is sold back; whereas, when the load is increased to 150% of nominal, only 21% is...
sold back to the utility. Previous studies (Reference 4) have shown that the load variations have very little effect on LCCR at sellback ratios of 50% or greater.

Design Performance

The monthly performance of the nominal design PV system is shown in Figure 3-8 for Boston and Madison with the design collector area of 51.3 sq.m. While the load curves represent total electrical demand, their shape clearly reflects the difference in regional climates between Boston and Madison, and the resulting space conditioning loads. Despite the latitude similarity, Madison generally experiences colder winters and milder summers than Boston; however, Madison has higher levels of insolation than Boston has due to coastal cloud cover. The overall effect of these conflicting regional factors tends to be offsetting with respect to the percent of load supplied directly by the PV system. In both locations, 25.3% of the load is supplied directly by the PV system.
Figure 3-8 PV System Monthly Performance Summary
SECTION 4
HOUSE DESIGN CHARACTERISTICS

Design Features

A passively heated house has been designed by Massdesign for the Northeast region of the country. The house is configured to maximize the amount of south glazing, while simultaneously providing a large rectangular roof for the PV system and it incorporates energy conservation features.

The house has two stories and a full basement. On the first floor is a large area containing the kitchen, dining room, staircase to the second floor, and living room. Also on the first floor on the east end of the house is the master bedroom suite, with a full bath, a dressing room, and a sliding glass door facing south. On the second floor are two additional bedrooms and a bath. Both bedrooms and the connecting hall are illuminated from clerestory windows above the PV roof. The total floor area of the house is 157 sq.m. On the south side of the living space is an 8.9 sq.m. greenhouse. A large brick fireplace wall, which also provides massive storage for solar heating is located at the core of the house, on the north side of the living room. The basement is not subdivided, but is completely insulated around the walls and under the slab. All of the electrical equipment for the PV array and the house panel is located in the southwest corner of the basement. An airlock entry is provided on the north side.

Although any of a number of energy conservation construction methods are applicable to the building, it is designed around the innovative Acorn Structures, Inc., building system. Massdesign has been working for several years with the Acorn systems, and has assisted Acorn in developing an effective
and economical method for providing a high level of energy conservation.

Because the system relies upon components trucked to the site, a minimum of wood is used. The walls are 2 x 4 stud construction, at an average spacing of 16 inches on center, with R-11 insulation. On the inside of the walls, an additional 3/4 inch of "Thermax" (trade name) foil-faced polyisocyanurate insulation is used, yielding an extra R-factor of 6. The combined wall section resistance value is 19. The combined cathedral ceiling R-factor is 28. This total R value includes 7 inches of fiberglass in the ceiling (limited by a 2 inch air space under the PV array), for an R-22 value, plus an inside layer of Thermax for an additional R-6 value. Attic space ceilings are insulated with R-30 insulation, and R-11 insulation is used between the attic and the adjacent bedrooms. South windows are all double glazed and the remainder of the windows are triple glazed. Motorized draperies are used across the entire south facade in the living and dining spaces. These draperies provide an additional R-factor of 5 when they are closed.

Infiltration is minimized as much as possible in the design. The Thermax interior skin provides an excellent vapor barrier and a large measure of infiltration control. In addition, a great deal of caulking is also used. Because the Acorn house modular sections are made from kiln lumber and are built to tolerances of 1/16 of an inch, the building is intrinsically solid and tight, resulting in a low infiltration rate.

House Plans

Figure 4-1 shows two possible site plan arrangements of the house, one with an entry from the west (or east, if the plan is reversed), and the other
Figure 4-1. Site Layout for Northeast Passive House
with an entry from the south. By strategic location of the garage and the 
addition of a trellis to mark the location of the entrance, both plans can 
easily be accommodated and a third, north entry design, can be incorporated.
Flexible site plans are important, since a solar house has to face south 
independent of the street location.

The basement floor plan (Figure 4-2) has not been subdivided, but 
provides space for a shop, recreation area, or other non-habitable space which 
is valuable to a homeowner. The entire basement is insulated with R-11 
insulation, and the underside of the slab is insulated with R-5 insulation. All 
of the electrical equipment is located in the southwest corner of the basement 
on both the west and south walls. Both the normal electrical service and PV 
service enter on the west wall and penetrate diagonally through the wood 
structure, coming out of the inside of the foundation wall. The heat pump 
indoor section is located near the fireplace foundation, at the center of the 
plan, minimizing duct runs.

The first floor plan (Figure 4-3) is organized around a large central 
entry hall. The north airlock entry vestibule has ample closet space. Inside, 
the entry hall floor has quarry tile, and another large storage closet is 
located to the west. This hall opens to the kitchen/dining area, the living 
room, the master bathroom or the master bedroom and the stairs to the second 
floor. The master bath has two doors, making it accessible to visitors on the 
first floor. The fireplace is located at the north end of the living room so 
that the flue does not need to penetrate the roof area reserved for the PV 
array. It is also partially free-standing in the middle of the plan. The 
kitchen is located under the ordinary 2.4 m ceiling. It is open to the dining 
room which has a cathedral ceiling rising up to the second floor under the PV
array. This cathedral ceiling continues along the south wall, interrupted by the staircase, so that half of the living room is under the low ceiling, and the other half is under the cathedral ceiling. Figure 4-4 shows that the landing of the staircase has a railing looking down into both the dining room and into the living room. This feature provides an element which is highly favored by buyers. The staircase is located close to the windows, but leaves sufficient room for a walkway. Both the dining room and the living room are accessible to the greenhouse, which is centered to the south of the staircase by means of sliding glass doors. The second floor plan (Figure 4-5) shows the layout of the bedrooms and storage area.

Elevation views of the house are shown in Figures 4-6 through 4-9. In cross-section, the house features a roof with a shortened slant height. This permits the addition of a set of clerestory windows at the top of the PV roof. By somewhat complicated framing, the second story is placed under the high part of the section, and receives the benefit of the clerestory windows. The long north roof returns back to the first level, forming a large attic over the master bedroom, master bath, and entry areas. At the northwest corner of the building, the long sloping north roof is cut away to expose a two-story high section. The entry occurs at this point, and is designed for ready access from the north and west (and from the east if the plan is reversed). By extending a covered walkway, or trellis, out beyond the end of the plan, it is also possible to enter the building from the south. These options are shown on the site plan.
Figure 4-2. Basement Plan
Figure 4-3. First Floor Plan
Figure 4-4. Section View
Figure 4-7. East Elevation
Figure 4-9. West Elevation
Description of the Passive Solar Heating System

Figure 4-10 illustrates the four passive and auxiliary heating and cooling air flow patterns.

1. **Storing Heat from the Greenhouse** -- Solar energy penetrating the glazing of the greenhouse can heat the greenhouse, and be stored or directed to the living space of the house. There is an insulated thermal storage slab, in the greenhouse proper, which provides part of the desirable storage. In addition, overheated air from the greenhouse is directed into the far side of the basement by a small supply fan whenever the greenhouse overheats. These fans are under the control of a high limit thermostat located near the top of the greenhouse. This design uses the existing mass in the insulated floor slab of the basement, the finished materials of the basement, and the chimney foundation to absorb any overheating from the greenhouse instead of providing massive construction between the house and the greenhouse. This provides two benefits: (1) a warm basement; and (2) heat gain to the main living space from the first floor (as opposed to a loss if the basement were cold). This approach appears cheaper than providing a dedicated storage device in the basement for the greenhouse.

2. **Direct Gain with Intrinsic Storage** -- The normal passive operating mode of the house involves direct gain through the south glass with distribution into all major spaces in the house. While no special storage mass is included in the living space, the chimney mass is available to receive indirect radiation; and the framing, gypsym board and flooring provide a modest amount of storage. Aside from the greenhouse (which can receive much more heat than it needs during a sunny day), the rest of the house is "sun tempered" rather than passively solar heated. This means that only a modest amount of south glazing is included, sized to the modest amount of storage available in the intrinsic construction of the building. Much of the direct gain in the living spaces comes, secondarily, through the greenhouse by way of the sliding glass doors between the greenhouse and the living spaces.

3. **Auxiliary Heating from the Heat Pump** -- Whenever passive gain is unavailable or inadequate to satisfy the heating demand for the house, the heat pump operates in a normal fashion. In addition, the heat pump can be run without the coil, using the fan to redistribute air throughout the building during periods of direct gain. This further extends the effectiveness of the direct gain solar heating, as it allows all of the intrinsic structure mass to store excess passive gain. This process is not as efficient as direct storage in massive interior walls or trombe walls, however, the high cost and construction difficulties involved in building with these massive walls offsets their advantages. This redistribution approach is a simple means of increasing the solar gain with no added cost since the distribution system for the heat pump is already in place.
4. **Natural Cooling** -- The house is designed to provide the maximum amount of natural cooling and minimize the operation of the heat pump during the summer. First, the sloping glass in the greenhouse is permanently covered during hot weather with an insulating cover, either outside (taking account of the high maintenance requirement) or inside the glazing. Inside the glazing, the cover will either have a white or reflective outer surface to avoid excess buildup of heat underneath the double glazing. In the house, the primary cooling device is the row of awning windows forming a clerestory. The high clerestory windows induce a substantial flow of air through the house, since the amount of thermal siphoning ventilation is proportional to the height differential between the intake and discharge of air. These windows are controlled manually by the owner. Typically, the windows are open all the time during the warm weather and closed only when it gets cool or is extremely hot and humid during the day. The basement is also included in the ventilation of the house. Operating the distribution system without the coil allows the mass in the basement to function as a heat sink and help absorb some of the excess heat during the day. This will keep the house comfortable until cool night air is introduced by thermal siphoned ventilation. Backup cooling is provided by the heat pump.

Appendix D describes calculated estimates for the reduced heating loads due to the passive house design features.
Figure 4-10. Operating Modes for Passive and Auxiliary Heating and Cooling
The fireplace is included in the design primarily because of the intense market demand for fireplaces in a house of this price range. A wood stove could be substituted for the fireplace with no change in the design. Most of the chimney mass is interior to the house, with only the minimum chimney extending above the roof. A gasketed flue top damper operated by solenoid is included in the chimney to trap the air in the chimney and prevent the chimney from being cooled by convected loss up the flue. The heat that has accumulated in the chimney mass is then free to discharge into the space by radiation. By covering the embers of a fire with a tight fitting metal hood, it is possible to close the damper immediately after leaving the room, without having to leave the flue open until all the embers are cooled. This strategy also greatly increases the efficiency of an ordinary fireplace. If a wood stove were used, it would be likely that the chimney would consist of a metal flue extending above the roof. Masonry would be added around the flue on the inside of the building to provide the desirable thermal mass. While the flue top damper is not an ideal solution to the fireplace chimney problem, it does go a long way toward reducing convected losses during cool-down periods.
The residential solar array design for this Northeast application uses the GE rectangular shingle module in an 8 series by 7 parallel circuit configuration. The modules are presently under development by GE. These modules utilize a 9.4 cm. square silicon solar cell. The shingle modules are shown in detail in Figure 5-1. There are two module types, a full size module and a half size module. These physically different shingles are manufactured to the same specifications, except that the full module is twice the power at the same voltage as the half module. The solar cell network of the full module consists of 2 parallel connected rows of 48 cells wired in series. This constitutes a total of 96 solar cells per full module. On the other hand, the solar cell network of the half module, consists of 48 series connected cells. The construction details of the shingle modules are discussed in appendix F.

This shingle design is markedly different from the Block IV design described in Reference 4. The current shingle interconnection scheme uses the UL-approved AMP, Inc., flat-conductor cable (FCC) under carpet interconnecting system. The use of this flat conductor cable and patented crimp connector (see Figure 5-2) as the two output terminals of the module permits the reliable series parallel interconnection of modules on the roof at a lower total installed cost when compared to the original JPL Block IV design, which employed copper foil conductors within each module. The four terminals of this previous design were interconnected with machine screws to complete the series/parallel
Figure 5-1. GE Square Shingle Design
matrix on the roof surface. This AMP interconnection system also provides the ability to accommodate relatively larger variations in the placement of the modules on the roof and simplifies the module removal and placement procedure as will be explained later in the Array Installation section.

The module design characteristics at standard operating conditions are summarized in Table 5-1 for both the full and half shingles. The I-V trace for the full sized shingle is shown in Figure 5-2.

Table 5-1
Summary of Design Characteristics for the Rectangular Shingle Modules

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Configuration</strong></td>
<td>Full Shingle</td>
</tr>
<tr>
<td>Solar Cell Shape</td>
<td>---</td>
</tr>
<tr>
<td>Solar Cell Size (m)</td>
<td>---</td>
</tr>
<tr>
<td>Number of Solar Cells</td>
<td>96</td>
</tr>
<tr>
<td>Total Solar Cell Area (m²)</td>
<td>0.866</td>
</tr>
<tr>
<td>Exposed Module Area (m²)</td>
<td>0.916</td>
</tr>
<tr>
<td>Module Packing Factor</td>
<td>---</td>
</tr>
<tr>
<td>Average Maximum Power Point at SOC (kWp) NOCT = 65°C</td>
<td>74</td>
</tr>
<tr>
<td>$P_{MAX}$ (W)</td>
<td>---</td>
</tr>
<tr>
<td>$V_{MP}$ (V)</td>
<td>---</td>
</tr>
<tr>
<td>Areal Specific Output</td>
<td>---</td>
</tr>
<tr>
<td>(Watts/m² Module Area)</td>
<td>---</td>
</tr>
<tr>
<td>Module Weight (kgms)</td>
<td>18</td>
</tr>
</tbody>
</table>

5-3
Solar Array Characteristics

The solar array subsystem consists of an 8 series by 7 parallel module network covering the 5.1 m by 11.1 m roof. The total active array area is 50.2 sq.m. The solar array consists of 52 full shingle and 8 half shingle modules. The adjusted full shingle total is 56 modules. Eight modules are positioned along the roof slant height while seven modules are placed along the roof's horizontal dimension. The overall array layout is shown in Figure 5-3. The module to module electrical interconnections between overlapping layers form the series parallel matrix of shingles and are shown schematically in Figure 5-4. The voltage increases as modules are added in the series direction along the slant height of the roof from eave to ridge. The current increases as modules
Figure 5-3. Overall Array Layout
Figure 5-4 Solar Array Module Interconnection Electrical Schematic

are added in the parallel direction across the length of the roof from gable to gable. The negative terminations at the eave and the positive terminations at the ridge for each solar cell circuit are attached to the FCC busbars running the length of the roof.

Each module has a SOC average maximum power output of 74 W at 16.6 Vdc at an NOCT of 65 degrees C. Thus, the total maximum power output for the array subsystem is 4144 W. The array voltage at maximum power output is 132.8 Vdc. The I-V characteristic curve for the array subsystem was previously shown in Figure 3-3.

Solar Array Installation

The GE shingle module is classified as a direct mount system
installation. It is designed to serve as a weather-tight element and provide PV dc power. A PV array constructed with these modules as building blocks becomes the roof of the residence and displaces the need for conventional asphalt shingles. Figure 5-5 shows the overlapping installation of the shingles in a schematic diagram. Appendix C lists some general safety notes to follow during system installation.

Before shingle installation, the plywood roof sheathing is prepared with a Type 30 roofing felt, as in a typical residential asphalt shingled roof. A horizontal and vertical network of #10 AWG FCC cable is placed on top of the felt in accordance with the spacing requirements specified in Figures 5-6 and 5-7. The positive and negative buses each consist of three runs of FCC cable connected at intermediate points developing a tapered busbar effect. The negative busbar is folded and run up the left side of the roof to the roof ridge as shown in Figure 5-6.

All the FCC cable rows can be secured to the roofing felt with duct tape strips in their proper alignment prior to erection of the shingles; or they can be placed sequentially as the installation progresses up the roof. Dimensions of FCC cable rows detailed in Figure 5-6 are to the FCC center lines. The placement of the cables does not have to be held exactly to the dimensions. The cable row dimensions are identified as a guide so that shingle attaching nails will clear the FCC cable.
Figure 5-5 Installation of the GE Rectangular Shingle Module
The shingle installation begins with a dummy course of shingles placed at the roof's eave in the manner shown in Figure 5-8. Dummy shingles are electrically inactive shingles to complete a weather tight installation. They are fabricated with the exact same dimensions as the full and half sized active shingles. The dummy shingles are attached to the roof sheathing by nailing through the substrate at two marked locations, per shingle, with roofing nails. Following the dummy shingle course installation, seven full modules are overlaid constituting the first active row.

The active shingles are attached to the roof sheathing by use of a special split washer under the roofing nailhead as shown in the details of Figure 5-9. Two through holes which are larger than the nailhead but smaller than the washer diameter, are provided in the module substrate at specific locations. The split in the washer must be oriented up the roof with the removal slot positioned down the roof. The orientation of the washer is important and must be maintained. Upon completion of shingle installation, should it become necessary to replace a defective module, the washer can be removed by using a slender hooked tool. The shingle can then be lifted over the roofing nails allowing it to be slipped from under the overlapping shingle. The fold in the FCC cable, as shown in Figure 5-9, can be extended and the FCC cut. A replacement module can be reconnected with the AMP splice connector and the module reinstalled.
Figure 5-6. Horizontal FCC Cable Spacing Requirements
The negative leads from the first active row of shingles are connected to a single run of the triple layered negative FCC bus cable as indicated in the second step shown on Figure 5-8. The positive leads from the first shingle row are connected to FCC cable row B as shown in step three of Figure 5-8. The positive and negative shingle leads are connected to the horizontal FCC cable rows after nailing the shingles in place. All electrical connections and FCC cable terminations are covered with a two-piece insulating patch, detailed in Figure 5-9. The glass portions of the shingles are secured by an adhesive on the back surface of the module to prevent module lifting during wind conditions.

Subsequent rows of shingles are attached in a similar manner. Figure 5-10 shows typical array connections on the roof. The positive leads of the eighth active course of shingles terminate in a shingle run of the triple layered positive busbar identical to the negative busbar connections. The positive and negative buses are dressed through the roof to an AMP supplied transition block shown in Figure 5-9. This block provides the transition from FCC cable to the conventional cable. The remaining portion of the roof above the eighth course is then covered with two courses of dummy shingles. Figure 5-11 shows additional details at the edges of the installation.

At the completion of shingle installation, gable edge strips are applied to provide a weather-tight seal. The FCC electrical interconnection system has been successfully installed at the Northeast and Southwest Residential Experiment Stations with the GE Block IV-A shingle module.
Power Conversion Subsystem (PSC)

The power conversion subsystem, with the associated cabling and switchgear, provides the interface between the residential roof photovoltaic array and the normal residential utility service and loads. Functionally, it must convert the available array dc power to a usable and acceptable ac form. A line commutated inverter manufactured by the Gemini Corporation and marketed by Windworks, Inc., of Mukwonago, Wisconsin, is available in the 4 kVA range and therefore selected for this application. It can be supplied according to the specification included as Appendix A to meet the preferred control options. The PCS is packaged in three units: the inverter, dc filter and transformer, along with the control circuitry. Standard controls, filters and isolation transformer options are provided by Gemini to encompass the requirements specified for the residential design. Procurement of the basic inverter bridge, desired controls, filter, and transformer from a single source is recommended to assure compatible matching of PCS components.

Subsystem Requirements

The dc to ac conversion must be accomplished in a manner consistent with residential electric practice. The conversion techniques should accommodate the large range of solar array electrical parameter variations and residential load and utility line voltage variations. The interface must provide safe interconnections under all operational and failure modes and must provide feedback of any excess array power to the utility. Equipment selection should use proven technology to the extent available.

The requirements for converting the variable dc power and voltage of a
Figure 5-10. Typical Electrical Array Connections
Figure 5-11. PV Shingle Edge Installation Details
photovoltaic array to the utility residential fixed ac voltage low impedance interface can be reliably and economically met by solid state electronic inverter device, acting as a current source to transfer power. Although either self- or line-commutated inverters can meet the requirements, the latter is selected for this application. The line-commutated inverter, however, as applied to this residential system has the inherent disadvantages of poor power factor and high harmonics. On the other hand, it has a large technology application base and has been applied and tested in PV applications by several installers.

Subsystem Sizing

Array IV characteristics are shown in Figure 3-3 at SOC conditions. The characteristics indicate a maximum power rating of 4.1 kW and rated voltage of 132.8 Vdc at NOCT. The array maximum power point and associated voltage exhibits a dynamic variation with insolation, temperature and wind variations. The array maximum power point and voltage is examined on an hourly basis for Boston based on TMY weather data. Figures 5-12 and 5-13 illustrate the distribution of the maximum power and maximum power voltage, respectively, as a function of the array annual energy for Boston. These curves represent the array/PCS interface requirements.

Note that the array open circuit voltage under start-up conditions is significantly higher than the maximum power point operating range limit of 188 Vdc. The initial high open circuit voltages during start-up has been a problem for the prototype units under test at the Residential Experimental Station.
Figure 5-12 Integral Power Distribution of the Solar Array for Boston

Figure 5-13 Integral Voltage Distribution for the Solar Array in Boston
The annual distribution curves for maximum power and voltage in Boston, Figures 5-12 and 5-13, can also be used for subsystem sizing specification and operating voltage specification. The power distribution curve of Figure 5-12 indicates that 6.30 MWh of annual energy is generated at a 4 kW array rated level or below. The figure also shows a system peak power output of 5.28 kW. Only 2.2% additional energy is generated above the 4 kW power level. This implies that selecting a standard size 4 kW output rated PCS, captures nearly all of the available energy. (A 4 kW output rated inverter, assuming an average inverter efficiency of 87%, would accept input power levels up to 4.6 kW). The input power duration curve, Figure 5-14, indicates only 300 hours of the total annual operation at a power level of 4 kW or greater. This further substantiates the selected inverter size.

Figure 5-13 shows a wide swing of the system maximum power point voltage from 136 to 189 Vdc. The voltage can be expressed around the mid-point of the range as 162 ± 17% V. Accommodating the wide input voltage range usually results in poorer efficiency, poorer power factor and higher harmonics in the PCS design. Since the curve is "S" shaped with relatively flat ends, the maximum power voltage range can be limited with minimal loss of energy. Hourly simulation analyses, with excursion limits placed upon the maximum power voltage of 168 ± 7% V, are shown as the dotted curve in Figure 5-13. The annual energy collection with these limits is 99.1% of the unrestricted case. Thus, a voltage limit of 168 ± 7% Vdc input to the inverter is selected to enhance inverter performance with minimal annual energy collection losses.

These summary requirements have been analyzed for this Northeast residential design and detailed in a specification as referenced in Appendix A. Technical characteristics for the PCS are summarized in Table 5-2.
Table 5-2

PCS Characteristics

<table>
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<td>Nominal Input Voltage</td>
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<td>Full Load Power Factor</td>
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<td>Full Load Harmonic Distortion</td>
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<td>Full Load Audible Noise</td>
<td>50 dB @ 1 meter</td>
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<td>RFI</td>
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<td></td>
<td>From 5 kHz to 3 mHz</td>
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<td>Relative Humidity</td>
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<td>WIDTH(cm)</td>
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</tr>
<tr>
<td>Transformer</td>
<td>61</td>
<td>30.5</td>
</tr>
</tbody>
</table>
Figure 5-14 Power Duration for PV Array for Boston

PCS Specification

The system schematic diagram, Figure 5-15, establishes the interconnection of the PCS to its interfaces. The PCS consists of an inverter with control circuits, a dc input filter and transformer.

Inverter Specification -- The major item within the inverter is the conversion circuit. The inverter conversion circuit consists of a SCR thyristor bridge with SCR phase angle firing control electronics and initial adjustments for voltage and current limit settings. Commutation of the SCR's is accomplished by the reversal of ac line voltage as seen by the bridge circuit through the transformer, hence, line commutated. The phase angle firing control point is dynamically adjusted within limits to transfer the maximum available array
Figure 5-15. Interconnection Diagram
power. The initial adjustments provide for three set points: dc turn-on voltage, IV load line slope, and current limit. These adjustments are described below.

1. DC turn-on voltage -- This adjustment determines voltage input below which no power inversion takes place. This assures that the array source will have useful output before any loading takes place. Adjustment of this voltage is dependent upon the system characteristics and for this design it is set for 120 Vdc nominal.

2. Current limit -- This adjustment determines the maximum dc current that will be converted to ac and is essential for protection of both the power source and the inverter circuitry. Excessive current can be harmful to the components of the inverter or to the wiring or distribution equipment. Current limiting is accomplished by sensing the dc current and adjusting the switching action to avoid any excessive current.

3. IV Load Line Slope -- This adjustment determines the pattern of current rise that occurs as the voltage increases beyond turn-on voltage as described above. As the voltage increases, more and more current is converted to ac up to the point where current limiting action occurs. The amount of voltage increase from the turn-on voltage to the value at the current limit point is the current slope voltage.

Suitable fusing is also included on the dc input to the bridge circuit and the ac output from the bridge circuit.

Start-up/Shutdown -- The control circuitry for daily operation is shown in Figure 5-16. The inverter will operate in its normal mode when the main on/off switch, S1, is closed. The operation is illustrated by following the sequence of circled numbers around the diagram. In the morning when the sun rises, the array dc voltage rises exponentially. It should be noted that the array open circuit voltage is significantly higher than the maximum power tracking range. A sensitive relay or solid state logic circuit, C, closes the circuit for the ac input contractor B. AC line voltage, L1 and L2, will then operate the dc input contractor, A, permitting the inverter to transfer power. If either L1 or L2 should fail, contractor A opens, thus shutting the inverter.
Automatic operation for $V_{DC} > V_{DC\text{ MIN}}$
Automatic shutdown on AC line loss
No AC load in off condition

Figure 5-16. Power Conversion System Interface
down. Auxiliary logic and timing controls verify a net power output on start-up. For no net power output, the inverter shuts down again for a preset short period to avoid rapid cycling. When the sun sets, the inverter shuts down for the night due to net power less than zero. This evening shutdown and opening of the ac line contractor eliminates night-time no load losses on the transformer.

**Maximum Power Control** — The operation of the maximum power tracking controller is based upon the photovoltaic power-voltage characteristic shown in Figure 5-17. A simplified block diagram for this tracking controller is shown in Figure 5-18. The basic elements include:

1. A wattmeter circuit that continuously measures the power level and provides a signal output proportional to actual power.

2. Two sample and hold circuits, controlled by a timer, that alternately sample the wattmeter signal output and hold it for comparison with the next sample.

3. A comparator that works in combination with a logic circuit to determine if a given sample represents a power level that is greater or smaller than the previous sample.

4. A flip-flop circuit that changes state whenever a new sample is smaller than the preceding one, but remains in the same state if a new sample is larger than the preceding one, thus representing an increase in power level.

5. An integrator circuit that provides a constantly changing output, whose direction of change is increasing for one state of the flip-flop and decreasing for the other state of the flip-flop.
Figure 5-17 PV Power Characteristics

Figure 5-18 Simplified Block Diagram of Gemini Maximum Power Tracking Controller
The output of the integrator is the signal which controls the input voltage level to the Gemini. It has limits which are set so that it does not attempt to control voltage beyond the tracking limit set-points. The integrator constantly changes its output in a direction determined by the state of the flip-flop. If, for example, the flip-flop is forced to remain in a state that causes a constantly increasing output of the integrator, the Gemini will sweep through its voltage range starting at a low level and increasing to maximum as determined by its preset limit. If the state of the flip-flop is changed and forced to remain in the opposite condition, the integrator signals the Gemini to sweep down the curve toward zero.

In automatic operation, the flip-flop is not held in any particular state, but is allowed to change as determined by the interpretation of successive samples. The sample rate is adjusted so that many samples are taken in the time it would take the Gemini to make a complete sweep from minimum to maximum or from maximum to minimum.

If the Gemini starts at zero voltage and is moving in a direction toward maximum voltage, as each sample is taken, the logic circuit and the comparator compare it to the preceding one. On the short-circuit current side of the maximum power point as the voltage increases, each sample of power is larger than the one before it, and the flip-flop does not react. The voltage, therefore, continues to rise. Eventually the voltage reaches the value corresponding to maximum power point and passes through it. When this happens, the next sample of power indicates to the logic circuit and the comparator that the power has decreased from the preceding sample, and the flip-flop changes state. This causes the voltage to stop rising, reverse movement to a downward direction, and return toward the maximum power point.
From this time on, the voltage cycles back and forth around the maximum power point, reversing direction each time it moves far enough to indicate a decrease in power. If the source characteristics or output changes, an automatic readjustment stores the Gemini voltage control to the new optimum point. To provide minimum voltage swings in the area of maximum power and to allow optimum stability, the rate of voltage change as well as the time between samples, is adjustable.

**DC Input Filter and Transformer Specifications** — The remaining two packages of the PCS are the dc input filter and the transformer. The dc filter inductor serves the function of maintaining current flow through the conduction portion of each thyristor commutation cycle. This reduces the current harmonics to levels acceptable for use or further filtering if required. Windworks provides the filter package to match the inverter and power ratings.

The third package of the PCS is the transformer. The transformer serves the dual function of providing isolation of dc array output and the ac line and matching of the ac line voltage to the dc voltage for proper commutation. Isolation of the sources is a mandatory circuit requirement when a grounded dc bus is used in the array design. The negative bus is grounded in this design, thus requiring an isolation transformer.

The transformer will be rated higher than the inverter bridge and PCS as a whole to accommodate the out of phase ac voltage and current. A nominal rating of 5 kVA for the transformer is suitable for accommodating the anticipated power factor of operation.
PV Array Electrical Interface to Conventional House System

The basic approach for design of the interface arrangements is to employ conventional wiring runs and equipment in a manner to maximize safety in accordance with the National Electric Code requirements. Since the PV system is a self-generating source of electricity for the residence, it must be interpreted as an electrical service and is treated in the same manner as the utility service.

The array positive and negative FCC buses are brought down through the roof approximately 25.4 cm down from the peak between the rake and exterior wall surface. The buses pass through a 2.5 cm raceway sleeve to the top of the transition block (AMP, Incorporated Part No. 80-32273) and box enclosure. Reference Figures 5-9 and 5-19 for transition block and roof rake details. The transition block converts the FCC bus cables to #6 AWG positive and negative bus conductors. These conductors pass through 2.5 cm PVC conduit and follow the ac utility service entrance cable to the exterior PV array disconnect switch. The PV service entrance is located at the same exterior wall as the utility service as shown in Figure 5-19. This visually separates the residence from one having only a normal overhead service and should alert emergency personnel that two power systems are in use.

Since the equipment area is located at an exterior wall, the PV disconnect could have been located inside the equipment room along with the utility service disconnect. However, exterior disconnect capability is preferable as it affords a visible break of the PV array supply. The disconnect switch includes fuses for overcurrent protection required by code requirements.
for electrical service devices. The PV array will generate a maximum of 110% of full load current, even if shorted.

The PV system schematic wiring diagram is shown in Figure 5-20. An additional unfused disconnect is provided in the equipment room at the dc service entrance location. This provides array isolation, and when used in conjunction with the disconnect switch between the inverter and ac house panelboard, allows safe maintenance on either the dc filter, inverter or transformer. The positive leg of the dc system is surge suppressed with a varistor connected to the array side of the interior disconnect switch. This varistor provides surge protection of the array, even if the interior disconnect switch is open. Beyond the indoor disconnect switch, all dc power is carried through a raceway system to the inverter enclosure. Electrical connections between the dc filter and inverter are conduit encased. Connections between the transformer and inverter are through 3.8 cm Greenfield. All other power connections from the inverter to the ac house panelboard are conduit encased. The service panelboard is provided with residential type lightning arrestors to provide output circuit protection to induced voltage surges.

An exposed copper house ground bus is located directly below the service panelboard. This provides a visible and accessible means for terminating all grounding conductors. The house ground bus is connected to the incoming water service as prescribed by the National Electric Code. An additional ground rod is provided should the water service ground be unsuitable.
Figure 5-19. PV Interface Arrangement
Figure 5-20. PV System Wiring Schematic
UL-labeled materials are used for all phases of the installation. All equipment is labeled and a copy of the schematic diagram will be posted in the equipment room. Appendix B lists the electrical system installation specification.

**Equipment Area Electrical Layout**

The equipment area contains all the major equipment associated with the power conditioning and distribution of the solar array power. This area is located in the southwest corner of the basement level. There is no need for a self-contained or enclosed equipment area.

Service entries to the equipment area from the outside disconnect switch and utility service meter are via thru-wall nipples. Equipment placement is in accordance with the equipment area plan as shown in Figure 5-21. Wall installed equipment is mounted on a 1.9 cm plywood backboard. This includes the panelboard disconnect switch, the house circuit breaker panelboard and lightning arrestors. The inverter and isolation transformer are floor mounted. A tabulation of major equipment is listed in Table 5-3. Appendix B provides the complete system installation specification.
Table 5-3 Major Electrical Equipment List

- Disconnect switch, fused, 2 pole, 60 Amp, 240 V, NEMA 3-R enclosure
- Varistor, GE Type V275LA40B
- Disconnect switch, non-fused, 2 pole, 60 Amp, 240 V, NEMA 1 enclosure
- Iron core swinging inductor, Gemini Corporation
- Inverter, 4 kVA, Gemini Corporation
- Isolation transformer, 5 kVA, Gemini Corporation
- Residence Circuit Breaker Panelboard
- Varistors, GE Type TLP175

Lightning Protection

The lightning environment for the Boston area is shown in Table 5-4. Due to the low isokeraunic level in the Northeast and the low probability of residential building lightning strikes per year, nominal protection utilizing surge arrestors will be installed on the positive array input terminal is services with a GE Type V275LA40B varistor. The utility bus is surged suppressed with GE Type TLP175 varistors. These varistor types provide inverter input and output circuit protection due to high voltage surges.
Figure 5-21. Equipment Room Layout
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<th>Isokeraunic Level</th>
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<tr>
<td>Flashes/Yr/sq.km</td>
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<tr>
<td>Flashes to Ground/Yr/sq.km</td>
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<td>Building Ground Plan Area (sq.m.)</td>
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<td>Building Strikes/Yr</td>
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<td>Equivalent to 1 Strike Every</td>
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<tr>
<td>100 m Radius Strikes/Yr</td>
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<tr>
<td>Equivalent to 1 Strike Every</td>
<td>32 Years</td>
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</table>
SECTION 6
SYSTEM DESIGN ALTERNATIVES

A logical extension to the present, highly energy conscious design is a solar domestic hot water system. This system would further reduce the total electrical load requirements on the house. This option was evaluated for a Northeast residence in the side-by-side PV/Thermal design report, Reference 15. In that design, approximately 8 sq.m. of thermal collectors reduced the hot water demand by 65% in Boston. This results in an overall reduction of 22% in the total electrical loads. The overall system economic viability and PV system size remains unchanged with this option, and the total yearly energy bill of the house is reduced. The amount of PV energy used directly in the house does decrease as indicated in Figure 3-7. For this specific house design, however, the roof area would have to be increased slightly or the PV array area would have to be reduced to accommodate the solar thermal collector area.

Similar results would also be expected if a hot water recovery unit was used to reduce the total electrical hot water requirements. This option was evaluated in Reference 16. The net reduction in the hot water demand would not be as significant as in the solar thermal hot water system, but no additional roof area is required.

Since all potential options could not be addressed in each design, the reader is directed to References 15 and 16 for more detailed discussions of these design options.
SECTION 7
REFERENCES


1980.

APPENDIX A

POWER CONVERSION SUBSYSTEM

SPECIFICATION
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<td>3.3.10</td>
<td>Documentation</td>
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SECTION 1
SCOPE

This specification establishes the requirements for the performance, design, construction and testing of a single-phase, three-wire, sixty hertz, utility-line, voltage-controlled, photovoltaic dc to ac power inverter with associated timing controls; hereinafter, referred to as the Power Conversion Subsystem or PCS. The PCS is intended for use in providing the power conversion necessary for a residential photovoltaic system application.
SECTION 2
APPLICABLE DOCUMENTS

The following documents form part of this specification to the extent specified herein. In the event of conflict between this document and the referenced documents, the more stringent requirement shall apply.

NFPS 70
National Electrical Code
SECTION 3
REQUIREMENTS

3.1 FUNCTIONAL REQUIREMENTS

3.1.1 GENERAL
The PCS shall invert the variable dc output of a solar photovoltaic array to supply residential ac electrical service in parallel with utility electrical service. The PCS shall be operated as a current source with an output ac voltage controlled by the utility line voltage. The PCS shall be capable of continuous operation and its rated input power. The PCS shall include a dc filter, inverter and transformer as shown in Figure A-1. The inverter shall include the inversion components, control logic for timing, automatic operation and power maximization, protective components, control switches, adjustments and indicators.
FIGURE A-1  INTERCONNECTION DIAGRAM
3.1.2 POWER CONVERSION SUBSYSTEM
The PCS shall provide the interface between the solar array dc output and the residential electrical service. The PCS will automatically start operation and connect the solar array to the service panel whenever the dc bus voltage exceeds the specified minimum value. The PCS shall automatically disconnect the solar array from the residential electrical service in the event of the loss of or out of tolerance utility line voltage or the absence of real PCS output power.

3.2 PERFORMANCE REQUIREMENTS

3.2.1 INPUT POWER
The PCS shall be capable of continuous operation at an input dc level of 168 volts and 26 amperes maximum; not to exceed an input power of 4 KVA.

3.2.2 DC TO AC INVERTER OPERATION
The dc to ac inverter shall provide to power conditioning necessary to convert solar power to usable ac service. The dc to ac inverter section of the PCS shall have the following operational characteristics.

3.2.2.1 Input Voltage Conditions
The PCS shall not initiate or continue dc to ac inverter operation whenever the real output power is zero or the ac voltage lines are outside the voltage limits required for normal correct commutation.

3.2.2.2 Startup/Shutdown Voltage
The PCS shall automatically initiate the closure of the output contactor and the inversion process whenever the dc input voltage rises above 156 Vdc and the ac utility service is within the voltage limits for normal correct
commutation. For voltages above 156 Vdc and less than 180 Vdc, the PCS shall maximum power track to within ±1% of the maximum power. The PCS shall automatically terminate the inversion process whenever the real output power is zero or the ac utility service is outside the prescribed voltage limits. Once operation has terminated due to the ac utility service being outside the prescribed limits, the PCS shall remain "OFF" for that period and for 4 minutes after the ac utility service return within the prescribed limits.

3.2.2.3 MAXIMUM POWER FEATURE
The PCS shall operate at the instantaneous maximum power point operating voltage of the solar photovoltaic array to within ±1 percent over the input voltage range from 156 to 180 Vdc. The PCS shall operate at 156 Vdc whenever the maximum power point is less than 156 Vdc and it shall operate at 180 Vdc whenever the maximum power point is greater than 180 Vdc.

3.2.3 SHORT CIRCUIT PROTECTION
The PCS shall be equipped with protective circuits or devices which will prevent damage to the PCS due to short circuit of the input or the output.

3.2.4 UNDervoltage and OVERvoltage PROTECTION
The PCS shall not be damaged by undervoltage or overvoltage conditions at the PCS input or output.
3.2.5 OPEN CIRCUIT PROTECTION
The PCS shall not be damaged by open circuit conditions appearing at the dc input or the ac output or both simultaneously.

3.2.6 EFFICIENCY
The PCS shall have an efficiency greater than 92% at the rated input specified in Section 3.2.1. Operating power losses shall not exceed:

- 150 Watts-Tare loss
- 3 Volts-Thyristor bridge loss
- 0.150 Ohms-Resistive loss

3.2.7 HARMONICS
The PCS RMS total harmonic content of the output current shall be less than 30% of the fundamental at the rated input specified in Section 3.2.1.

3.2.8 POWER FACTOR
The PCS power factor shall be greater than 60% at the rated input specified in Section 3.2.1.

3.2.9 CONTROLS AND INDICATORS
The following controls and indicators shall be provided on the front panel of the Inverter enclosure.
1. Inverter ON/OFF switch
2. Input current meter
3. Input voltage meter
4. PCS ON indicator light

3.3 DESIGN AND CONSTRUCTION

3.3.1 PHYSICAL CHARACTERISTICS

The PCS shall be housed in three wall or floor mounting enclosures meeting the requirements of the National Electrical Code. Enclosures shall provide access for installation, service, and maintenance. The three enclosures shall have maximum dimensions and weights as specified in Table A-1.

<table>
<thead>
<tr>
<th>Enclosure</th>
<th>Height (in)</th>
<th>Width (in)</th>
<th>Depth (in)</th>
<th>Weight (lb)</th>
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<td>16</td>
<td>16</td>
<td>120</td>
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<td>Inverter</td>
<td>30</td>
<td>24</td>
<td>14</td>
<td>60</td>
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<td>Transformer (5KVA)</td>
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<td>12</td>
<td>12</td>
<td>150</td>
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3.3.2 SERVICE CONDITIONS

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<tr>
<td>Ambient temperature</td>
<td>$0^\circ$ to $40^\circ$C</td>
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<td>Relative humidity</td>
<td>up to 95% noncondensing</td>
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<td>Barometric pressure</td>
<td>520 to 790 mm Hg.</td>
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### Non-Operating

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<td>Ambient temperature</td>
<td>-25°C to 60°C</td>
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<tr>
<td>Relative humidity</td>
<td>up to 95% noncondensing</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>520 to 790 mm Hg.</td>
</tr>
</tbody>
</table>

#### 3.3.2.3 Shock and Vibration

The PCS shall be constructed to withstand normal handling and transportation environments. Special packaging or restraints required for shipment shall be provided by the supplier.

#### 3.3.3 Grounding

Input and output circuits shall not be grounded within the PCS enclosures. Enclosure safety ground connections for interconnection to the service ground will be provided and identified by the supplier. Neutral wiring for the transformer secondary and primary may be specified as required.

#### 3.3.4 Life

The PCS shall be designed for a 20-year life with a minimum of maintenance. Any required preventive maintenance requirements shall be identified.

#### 3.3.5 Electrical Safety

The PCS design and construction shall conform to the applicable requirements and practices of the National Electrical Code (NFPA 70).
3.3.6 ELECTROMAGNETIC INTERFERENCE

Good design practices shall be followed to minimize electromagnetic interference and susceptibility. Conducted interference of the PCS shall be less than 200 microvolts between 5 kHz and 3 MHz.

3.3.7 AUDIBLE NOISE

Audible noise from the PCS shall be less than 50 dB one meter from the equipment when mounted in accordance with installation instructions.

3.3.8 THERMAL DISSIPATION AND COOLING

The PCS shall be designed to operate in the environment defined in Paragraph 3.3.2 without external cooling devices. Integral fans or blowers, if required, shall utilize ambient air. Interlocks shall be provided to shut the inverter down in case of failure of internal cooling devices.

3.3.9 MAINTENANCE

Accessibility

The PCS shall be designed to allow ready access for installation, adjustment, and maintenance. Insofar as possible, plug-in cards and modules shall be utilized to facilitate troubleshooting and repair.

Replacement

A listing of parts required to support the unit will be provided in the Operation and Maintenance Manual. This list shall identify those items required for operational support and maintenance.
3.3.10 DOCUMENTATION

Drawings
Schematics, wiring diagrams, and significant assembly drawing information shall be included in the Operations and Maintenance Manual.

Operations and Maintenance Manual
An Operations and Maintenance Manual shall be provided. It shall consist of the following:
1. General Description (a brief overall description of function and performance).
2. Installation Instructions (mechanical mounting and electrical connections).
3. Adjustment Procedures (set-up and calibration information).
4. Operating Instructions (description of operating controls and sequences).
5. Parts List (a list of applicable parts and replacement items).

Provision shall be made for permanent storage of the Manual in the inverter enclosure.
PASSIVE DESIGN NORTHEAST

RESIDENTIAL PHOTOVOLTAIC SYSTEM ELECTRICAL

INSTALLATION SPECIFICATIONS

PREPARED BY:

JOHNSON & STOVER, INC.

127 TAUNTON STREET

MIDDLEBOROUGH, MASSACHUSETTS 02346

FOR:

GENERAL ELECTRIC COMPANY
ADVANCED ENERGY PROGRAMS DEPARTMENT
P. O. BOX 8555
PHILADELPHIA, PA 19101

PREPARED UNDER

SANDIA CONTRACT 13-8779
ELECTRICAL SPECIFICATIONS

FOR

DETAILED RESIDENTIAL PHOTOVOLTAIC SYSTEM PREFERRED DESIGNS

DESIGN NO. 4

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PART 1: GENERAL REQUIREMENTS

1.1 GENERAL

A. This Specification includes all electrical work to install a roof-mounted photovoltaic (PV) system.

B. The system consists of several types of shingles which are to be interconnected by means of AMP Industries type FCC flat conductor cable.

1.2 REFERENCES

A. Cooperate and coordinate all electrical work with other contractors on site.

B. The complete structure will be constructed under another contract. The utility service will be in place along with the house circuit breaker panel-board and the customary house wiring system. The roof will be constructed and covered with roofing felt ready for shingle installation.

1.3 SCOPE OF WORK

A. Provide all labor, materials, equipment, and supervision necessary to complete the electrical work associated with a roof-mounted photovoltaic (PV) system, including all equipment identified.

1.4 WORK NOT INCLUDED

A. Construction of structure including roof underlayment and roofing felts.

1.5 QUALITY ASSURANCE

A. The work shall be executed in strict conformity with the latest edition of the National Electric Code and all local regulations that may apply. The installation of type FCC cable on a roof is not covered under Article 328 of the present National Electrical Code. The installation of the FCC cable shall be performed in strict accordance with manufacturer's recommendations and in accordance with the best practices of the trade. In case of conflict between contract documents and a governing code or ordinance, the more stringent standard shall apply.
B. Unless otherwise specified or indicated, materials and workmanship shall conform with the following standards and specifications (latest edition):

2. Occupational Safety and Health Act.
6. Local Codes.

C. Carry out tests, secure permits, pay fees, and arrange for all inspection of regulatory agencies for work under this section.

1.6 SUBMISSION DATA
A. Submit six (6) copies of all equipment to be incorporated into the work for approval prior to ordering same.

1.7 PRODUCT DELIVERY, STORAGE, HANDLING
A. All equipment, upon receipt, shall be inspected for damage and shall then be stored and protected from damage until project completion.

1.8 OPERATING INSTRUCTIONS AND MAINTENANCE MANUALS
A. Provide operating instructions to designated persons with respect to operation functions and maintenance procedures for all equipment and systems installed.

B. At project completion provide two (2) copies of bound brochures including all shop drawings, maintenance manuals, and spare parts lists.

1.9 ELECTRICAL CHARACTERISTICS
A. The PV array will produce an output of approximately 152.5 volts DC, which will then be inverted to a nominal voltage of 120/240 volts, single phase. Capacity of the system is approximately 4755 watts.
1.10 TEMPORARY LIGHT AND POWER

A. Provide temporary electricity from the existing house service as required to allow completion of the work. Remove any temporary wiring when no longer required.

1.11 RECORD DRAWINGS

A. Maintain two (2) copies of the documents on site and record any revisions on one set of the job progresses. At project completion, transfer all changes to the other set.

1.12 SAFETY PRECAUTIONS

A. The contractor shall be completely responsible for all safety precautions to be taken by installers of the array. Refer to Appendix "PV Module and Installation Safety Notes".
PART 2: PRODUCTS

2.1 RACEWAYS AND FITTINGS

A. Conduit - General

1. No conduit shall be used smaller than 3/4" diameter. No conduit shall have more than four (4) 90° bends in any one run, and where necessary pull boxes shall be provided.

2. Rigid PVC conduit shall be Schedule 40 UL listed for 90° C. All fittings shall be solvent connected. Provide threaded fittings where connected to metallic boxes. PVC conduit shall be Carlon. PVC conduit shall be used for exterior work and for raceways enclosing ground conductors.

3. Thin wall conduit (EMT), zinc coated steel, conforming to industry standards shall be used for all interior raceway systems. Fittings for EMT shall be compression or set-screw type. EMT shall be equal to Pittsburgh Standard Conduit Company, Republic Steel Tube, or Youngstown Sheet and Tube Company.

4. Conduit Fittings

a. Insulated bushings shall be provided on all raceways larger than 3/4".

b. Access fittings shall be Type LL, LR, or LB as required, and shall be equal to Appleton, Crouse-Hinds, or RACO.

B. Outlet, Pull, and Junction Boxes

1. Each outlet box shall have sufficient volume to accommodate the quantity and size conductors entering the box in accordance with the requirements of the National Electric Code. Outlet boxes shall be pressed steel as manufactured by Steel City, RACO, or Appleton.

2. Pull Boxes or junction boxes shall be constructed of code gauge sheet metal of a size not less than required by the National Electric Code, if no size is indicated on the drawings, and shall have hinged doors.

2.2 SUPPLEMENTARY STEEL, CHANNEL, AND SUPPORTS

A. Furnish and install all supplementary steel, channel, and supports necessary for the proper mounting and support of all equipment. Provide minimum of 3/4" thick plywood backboards for mounting of all equipment at the equipment area.
B. All supplementary steel, channel, and supports shall be UL approved, be galvanized steel, and be as manufactured by Steel City, Unistrut, Power Strut, or Kindorf.

2.3 CONDUCTORS

A. All conductors shall be stranded copper of the size indicated on the drawings. All conductors shall be Type THWN rated 90°C for dry locations and 75°C for wet locations.

B. Conductors for use on the DC system shall be color coded red for positive and black for negative. AC conductors shall be color coded black for Phase A, red for Phase B, white for Neutral and green for Ground. DC conductors shall also be identified as DC by label markers.

C. All conductor terminations shall be made up by standard lug connections on equipment having same. Terminations made up for attachment to positive or negative transition blocks at the roof and the DC input inverter or other devices not having standard lugs shall be bolted type compression lugs as manufactured by Burndy, Thomas & Betts, or Panduit of tinplated copper. Bolts shall be 1/4-20 silicon bronze.

D. All terminations, other than located within enclosures, shall be insulated.

2.4 SAFETY SWITCHES

A. Safety switches shall be general duty 2-pole or 3-pole fused or non-fused in NEMA 1 or NEMA 3R enclosures as indicated on the drawings and shall be capable of being padlocked. Switches shall be equal to General Electric, Westinghouse, or Square D.

2.5 GROUNDING SYSTEM

A. There shall be four (4) isolated ground systems as follows:

1. Grounded Neutral: The house wiring system neutral shall be grounded only at the house panel by means of a #8 AWG connection between the panel neutral bus and the panel ground bus. The panel neutral block shall be isolated from the panel enclosure. A #8 AWG green insulated ground conductor shall then interconnect the panel ground block to the house ground bus.
2. **Equipment Ground:** A #8 AWG green insulated ground shall be looped between all equipment and shall be connected to each piece of equipment by means of a ground lug on the equipment. This conductor shall terminate at the house ground bus.

3. **Varistor Ground:** The #14 AWG green insulated ground conductor from the Varistor shall be connected through a separate conduit system with the array negative ground. This ground shall terminate at the house ground bus below the house service panel.

4. **Array Negative Bus Ground:** Provide a #8 AWG green insulated ground conductor from the line side of negative bus terminal at the exterior mounted overcurrent device to the house ground bus below the service panel. Run in PVC raceway along with Varistor ground.

5. **House Ground Bus:** Provide a 12" long 1/8" x 1" copper ground bus on standoff insulators 12" above the floor below the AC panel. There shall be four (4) ground connections to the bus as follows: #8 AWG ground to house panel ground bus, #8 AWG ground to equipment ground system, #8 AWG ground at array negative bus, and #14 AWG ground for Varistor grounding. Provide a #8 AWG ground from the bus to the entering water service. In addition, provide a #8 AWG ground to a driven 3/4" x 10' long Copper Weld ground rod. This ground rod shall be located within the equipment area and shall extend 4" above the floor location.

6. **Varistor Surge Protection**
   a. Furnish and install a Varistor for surge protection, which shall be mounted in a junction box sized as required on the drawings. The junction box shall be provided with an insulated mounting block and terminal bar isolated from the metal structure. A #14 AWG ground wire shall be tap-connected to the positive DC conductor which is to be protected by means of Burndy Servit type KS split bolt connector. This connector shall be insulated by taping. The load side #14 AWG ground from the Varistor shall be interconnected to the house ground bus located below the house panel.
   b. Varistor on the positive DC side of the inverter shall be General Electric catalog number V275 LA40B.
B. Furnish and install a General Electric Lightning Arrester nippled to the side of the house service panelboard. Unit shall be catalog number TLP 175 and shall be connected with black leads to line buses and white to ground.

2.6 PHOTOVOLTAIC EQUIPMENT

A. The photovoltaic equipment including all shingle modules as shown on the drawings and including the roofing nails and split washers will be provided by General Electric Company.

B. The inverter package which forms an integral part of the generating and conversion system will be provided by General Electric Company and shall be installed by the Electrical Contractor.

C. FCC Cable System: The FCC cable, splice connectors, insulating patches, and crimping tool shall be as manufactured by AMP Industries and shall be furnished and installed by the Electrical Contractor.

D. Upon receipt of this equipment, each of the several parts shall be carefully examined to identify any possible shipping damages.
PART 3: EXECUTION

3.1 WORK COORDINATION AND JOB OPERATIONS

A. Be responsible for all equipment necessary for erection of the roof array including staging. Commencement of array erection signifies acceptance of the surface upon which the shingles are to be installed.

B. Coordinate all work prior to commencing with all existing conditions of the structure.

3.2 PLANS AND SPECIFICATIONS

A. The drawings showing layout of equipment, especially within the equipment area, show a suggested layout. Carefully check dimensions of all equipment and make any adjustments necessary to accommodate any variations.

B. Post the schematic diagram and equipment plan and elevation at a reduced scale under glass in the equipment area.

3.3 SYSTEM IDENTIFICATION

A. Provide screwed-on phenolic nameplates (black with white engraving) on all equipment. Differentiate between AC and DC equipment.

B. All raceways enclosing DC conductors shall be identified by appropriate labels.

3.4 WORKMANSHIP AND INSTALLATION METHODS

A. All work shall be installed in a first-class manner consistent with best current trade practices. All materials and equipment shall be securely installed plumb and/or level.

B. The inverter cabinet shall be mounted using Korfund vibration pads. All wiring connections to this cabinet shall be in flexible metal conduit.

C. All raceways shall be properly aligned, grouped, and supported at right angles to or parallel with the principal building members.

D. Any holes drilled through structure shall be neatly made and properly sealed after equipment installation.
E. All wiring in panelboards and enclosures shall be neatly formed and grouped.

F. Be responsible for all safety precautions and rubbish removal. Leave site in clean condition.

3.5 ARRAY ERECTION PROCEDURE

A. The roof will be wider than the array layout. The array, therefore, shall be centered on the roof. The excess roof area at the sides will be covered by flashing prior to the installation of the shingles.

B. It is recommended that the type FCC cable rows be secured to the roofing felts in their proper alignment prior to commencing erection of the shingles. Dimensions of FCC cable rows detailed on drawing E-2 are to cable center lines and are given exactly to the height each shingle row will advance up the roof. The connection of the shingle positive and negative leads allows some variation in the exact location of the cables. The cable row dimensions are identified so as to clear all nail holes. The positive and negative bus cable rows should be installed prior to connecting any shingles.

C. The positive and negative leads of the shingles shall be connected to the horizontal FCC cable rows prior to nailing the shingles in place. Nailing of the shingles shall be done by means of the nails and split washers provided. The opening in the washer shall be oriented in a straight vertical position to allow future removal of the shingle with the shingle removal tool. After the shingles have been secured in place, a bead of clear silicone sealant shall be applied to the bottom edge to prevent shingles lifting during wind conditions. The leads of the shingles are of sufficient length to allow removal of the shingle and reinstallation of a new single should it become necessary. After the shingle has been electrically connected and secured in place, the excess lead length shall be folded over on itself as indicated on Drawing E-6.

D. The positive and negative buses each consist of three (3) runs of FCC cable. The negative leads from the first row of "SCM" shingles and the positive leads of the top active row of "SCM" shingles shall each be connected to a single run of FCC cable. The second and third layers of FCC cables are then interconnected to the first.
E. The positive and negative buses shall be brought
to a transition block enclosure located on the
side wall via a pullbox to be located below the
clear story stool as indicated on the drawings.
The bus cables shall be pulled through the pull-
box and raceway to the transition block enclosure
prior to connecting any shingles and before the
final roof flashing is installed. Loosely secure
the pullbox to the vertical wall to allow flash-
ing to be later slid behind the pullbox and over
the FCC cables. After flashing in in place, re-
secure the pullbox and seal at all edges in con-
tact with flashing by means of silicone sealant.

3.6 FCC CABLE INSTALLATION

A. The horizontal and vertical rows of FCC cables shall
be secured to the roofing felt by means of duct
tapes approximately every 6'.

B. The positive and negative buses each consist of
three (3) rows of FCC cable which shall be in-
stalled on top of each other. Tape the cables to-
gether periodically prior to securing to the roof.

C. The horizontal runs of cables shall be terminated
with end seals.

D. Terminations and splicing shall be carried out in
accordance with the manufacturer's recommended pro-
cedures. Special connector assemblies will be pro-
vided along with an installation crimping tool. The
operation of the crimping tool is such that a posi-
tive connection is ensured prior to release of the
tool jaws. Each splice or connection shall be ins-
ulated by means of a manufactured two-piece insul-
ating patch.

E. Two transition blocks will be required and shall be
mounted by the Electrical Contractor in an approp-
riately sized NEMA 3R hinge cover enclosure on the
exterior.
APPENDIX C

INSTALLATION

SAFETY NOTES
APPENDIX C
INSTALLATION
SAFETY NOTES

It is recommended that the following safety precautions be enforced during all phases of array installation or shingle module replacement. The PV array can be installed during daylight hours. Each shingle module can generate a maximum potential of 25 Vdc. The series connection of modules up the slant height of the roof will provide a potential of approximately 200 Vdc from eave to ridge. Caution must be exercised to insure that no conductive path is provided across module terminals by installation personnel or equipment. The following list itemizes key safety requirements.

- No metal ladders or scaffolding should be used
- Installation should proceed only on a completely dry roofing surface
- The negative array ground terminal should not be connected until the electrical installation is complete
- The modules should be installed one course at a time from roof edge to roof edge, and not in any staggered pattern
- No electrically conductive material should be laid over the roofing surface during the installation
- The installation should be accomplished working from the roof surface as much as possible
- Grounded components, such as plumbing standard pipes, should not be touched and preferably they should be covered with an electrical insulating cover during the installation
- Care should be exercised not to make physical contact with module terminations across a multiple of installed shingles
APPENDIX D

PERFORMANCE SIMULATION

MODEL AND INPUT DATA
APPENDIX D

PERFORMANCE SIMULATION MODEL AND INPUT DATA

The simulation model is an adaptation of an analytical model developed during previous DOE-sponsored studies. The model permits the assessment of system performance on an annual basis using hourly SOLMET TMY data tapes as the input. The program calculates, for each daylight hour, the solar array operating point voltage and power using an iterative calculation procedure based on models for current-voltage characteristics, array temperature, insolation, and battery state-of-charge, as described below. The losses in the inverter are then determined based on solar array output power.

Solar Array Electrical Model

The synthesis of the solar array current-voltage characteristic, as a function of the total insolation on the surface and the solar cell temperature, is modeled based on a single cell characteristic which is represented by the following relationship:

\[ I = C \cdot E \cdot I_{SC} - \frac{V}{R_P} - I_o \left\{ \exp \left[ K (V + IR_S) \right] - 1 \right\} \]

Where
- \( I \) = Cell output current (Amperes/cm²)
- \( V \) = Voltage across cell terminals (Volts)
- \( I_{SC} \) = Illumination current (virtually equal to short-circuit current) (Amperes/cm²)
- \( C \) = Ratio of the total insolation incident on the solar cells to the reference insolation for the basic cell characteristics (100 mW/cm²)
- \( R_P \) = Shunt resistance of the cell (Ohms-cm²)
- \( I_o \) = Reverse saturation current of the ideal diode characteristics

\[
= \frac{V_{oc}}{R_p} - \exp (K V_{oc}) - \exp (K R_S I_{SC})
\]
K = Coefficient of the exponential (Volts⁻¹)
R_S = Series resistance of the cell (Ohms-cm²)
V_oc = Cell open circuit voltage (Volts)
E = Encapsulation loss or gain expressed as the fraction of bare cell short-circuit current

 ISC, RS, R_p, K and V_oc are represented by polynomials of the form:

\[ Y = a_0 + a_1 T + a_2 T^3 + a_4 T^4 + a_5 T^5 + a_6 T^6 \]

where
T = Solar cell temperature (°C)
Y = Dependent variable (ISC, RS, R_p, K, or V_oc)

The values of the coefficients are selected to represent the characteristics of the solar cells used in the module being considered. The total solar array output characteristics are calculated based on the single cell characteristic by multiplying the voltages and currents by the number of cells in series and parallel, respectively. In addition, the series resistance of panel wiring is accounted for in the array characteristic.

Insolation Model

The value for total insolation (direct plus diffuse) on the sloped surface is obtained from the values for the direct and diffuse components of the insolation on a horizontal surface as obtained from the SOLMET TMY data tape by applying the following relationship:

\[ H_T = H_{DIR} R_{DIR} + H_{DIF} [ \left( \frac{1 + \cos \beta}{2} \right) + \rho \left( \frac{1 - \cos \beta}{2} \right) ] \]

where
H = Total insolation on the sloped solar array surface
H_DIF = Diffuse component of the solar flux incident on a horizontal surface
H_DIR = Direct components of the solar flux incident on a horizontal surface
\[ \beta = \text{angle between horizontal and solar array surface} \]
\[ \rho = \text{the reflectance of the surrounding ground (a value of 0.4 was assumed in the analysis)} \]

The value of \( R_{\text{DIR}} \) is the ratio of the cosine of the solar angle of incidence \( (\theta_1) \) on the tilted solar array surface to the cosine of the solar angle of incidence \( (\theta_{1h}) \) on a horizontal surface. The value of \( \cos \theta_1 \) is determined as a function of the day of year, time of day and surface location and orientation in accordance with the following relationship:

\[
\cos \theta_1 = \sin \delta \left[ \sin \phi \cos \beta - \cos \gamma \cos \phi \sin \beta \right] \\
+ \sin \gamma \sin \beta \cos \delta \sin \omega \\
+ \cos \delta \cos \omega \left[ \cos \gamma \sin \phi \sin \beta + \cos \phi \cos \beta \right]
\]

where

\[ \theta_1 = \text{Angle of incidence of beam radiation measured between the beam and the normal to the solar array surface} \]
\[ \phi = \text{Site latitude (north is positive)} \]
\[ \delta = \text{Solar declination angle} \]
\[ \beta = \text{Angle between horizontal and solar array surface} \]
\[ \gamma = \text{Solar array surface azimuth angle (zero is due south, west of south is positive)} \]
\[ \omega = \text{Hour angle (zero is solar noon)} \]

For a horizontal surface this expression reduces to:

\[
\cos \theta_h = \sin \delta \sin \phi + \cos \delta \cos \omega \cos \phi
\]
Array Thermal Model

The temperature of a roof-mounted solar cell module was calculated based on natural convective cooling from the front surface of the module installation. Under this condition the heat balance equation for the solar cell modules is given by:

\[
[\alpha_s p + 0.3 (1-p) ] H_{TOTAL} = h_o (T_{cell} - T_{amb}) + \epsilon \sigma (T_{cell}^4 - T_{sky}^4) + h_{o2} (T_{cell} - T_{amb})
\]

where

- \(H_{TOTAL}\) = total insolation on the sloping solar array surface (W/m\(^2\))
- \(p\) = ratio of solar cell area to total module area
- \(\alpha_s\) = solar absorptance of solar cells
- \(T_{amb}\) = ambient temperature (\(^\circ\)K)
- \(T_{sky}\) = sky temperature (\(^\circ\)K)
- \(T_R\) = temperature of the living space under solar array (\(^\circ\)K) = 296\(^\circ\)K
- \(T_{cell}\) = solar cell module temperature (\(^\circ\)K)
- \(h_o\) = convective film coefficient on the module front surface, (W/m\(^2\)-\(^\circ\)K)
- \(h_{o2}\) = convective film coefficient on the module back surface, (W/m\(^2\)-\(^\circ\)K)
- \(\epsilon\) = hemispherical emittance of the front surface of the solar cell modules
- \(\sigma\) = Stefan-Boltzmann constant
  - \(\sigma = 5.6697 \times 10^{-8} \ W/m^2 \ ^\circK^4\)

The sky temperature, \(T_{sky}\), is calculated, using the relationship given in Reference 6:

\[
T_{sky} = 0.0552 (T_{amb})^{1.5}
\]
The front surface \(h_0\) and back surface \(h_{02}\) film coefficients are calculated using relationships given in Reference 14.

\[
h_0 = 1.247 \left( (T_{cell} - T_{amb}) \cos \beta \right)^{1/3} + 3.81 \ V \\
h_{02} = 1.079 \left( (T_{cell} - T_{amb}) \cos \beta \right)^{1/3} + 3.81 \ V
\]

where
\[
\beta = \text{slope angle of roof (measured from horizontal)} \\
V = \text{wind speed (m/s)}
\]

Compared with data reported by JPL in Reference 14 the analytical model tends to over-predict cell temperature, with the result that predictions of cell output contain a conservative bias.

**Inverter Loss Model**

The inverter loss model used in the battery storage analyses assumed a constant 87% efficiency. A more sophisticated model of inverter losses, used in the feedback analyses and accounting for constant loss, SCR bridge losses, and resistive losses, predicts efficiencies ranging from 85 to 90% on an hourly basis with an annualized efficiency of 87%.

**Battery Model**

The charge and discharge voltage of a hybrid lead-acid battery has been modeled as a function of battery state of charge (SOC) and instantaneous charge or discharge rate. Figure D-1 shows a set of these characteristics as modeled based on data supplied by C&D Batteries Division of the Eltra Company. The bottom set of curves are discharge characteristics with discharge rates varying from 0.02C to 0.2C, where C is the cell energy capacity in Ampere-hours. The top set of curves are charge characteristics at the same rates, assuming that recharge starts from the fully discharged condition. Different sets of characteristics are modeled for various battery SOC conditions. Since the battery is modeled on these actual characteristics, the round trip efficiency for the battery varies with battery capacity and collector area for the different cases analyzed. The average round trip efficiency was in the
Figure D-1. Battery Simulation Model
range of 75 to 88% which includes a constant average Ampere-hour charging efficiency of 0.952 based on the information from C&D Batteries. For a reference case of 65 m² cell area and a battery capacity of 20 kWh, the average round trip efficiency is 85%.

INPUT DATA

The PV system simulation model requires input data, representing the PV system characteristics and hourly histories of local weather, insolation, and residential electrical and space conditioning loads. Each of these input items is discussed below.

PV System Data

This data provides a description of the system in terms of its electrical characteristics. It includes such information as the number of solar cells in each series circuit and the number of parallel circuits. Cabling resistance and module interconnection resistance are also input for determining power losses from the DC output to the inverter input. A series resistance of 31 milliohms has been calculated for the current.

Weather Data

The National Climatic Center has recently made available rehabilitated, combined, hourly solar radiation and meteorological data for twenty-six sites across the United States. The solar radiation values from these SOLMET data sites have been corrected to reduce some of the major data errors and gaps, and to provide non-measured direct radiation data on the basis of the most recently developed correlation techniques with measured total radiation data. The SOLMET records provide up to a twenty-three year record for the selected sites.

Sandia recently prepared a synthetic Typical Meteorological Year (TMY) for each of the the twenty-six SOLMET sites. These TMY data tapes are based upon a selection of the most typical January, February, etc., available in the years of record for each site. Typical
months were selected by a weighting technique for insolation, temperature and wind speed. These TMY SOLMET records for all 26 sites are available at GE. They provide a real weather data base for solar system performance evaluation and comparison.

**Electrical Load Data**

Electrical loads for other than space conditioning are divided into three categories. The first category is diversified or base load demand and includes lights and many miscellaneous applications in the modern home. The second group includes cooking and clothes drying loads while the third grouping consists of heating loads for domestic hot water. Profiles of the integrated amount of energy used during each hour of the day for the various categories of energy usage were developed for 1977 by utilizing a wide variety of references. From the data examined, an annual usage of 5540 kWh was assumed representative of the diversified energy usage by a typical family of four persons in 1977. Since lights and some appliances (e.g., refrigeration equipment and HVAC auxiliaries) do have seasonal variations in their use, profiles for the four seasons were developed. No significant regional variations were found. The cooking and clothes drying profile was found to have negligible seasonal and regional variations, and their annual load was determined to be 2220 kWh for the 1977 time period. An annual hot water load was similarly determined at 4940 kWh but a regional correction was applied to both the hourly profile and the annual value to account for difference in ground temperature across the country. Seasonal variations were also incorporated.

All the profiles and annual values developed for 1977 were modified for projected usage trends in 1986 according to the rationale indicated in Table D-1.

It should be noted that the projected decrease in baseload usage is 1.8% per year reflecting a more dedicated conservation program than had been assumed for previous preferred designs. For the earlier designs, the projected baseload reduction was based on the average of two projected reductions. The current analysis used the higher projected reduction.
Table D-1. Seasonal Regional and Projection Adjustments of Loads

<table>
<thead>
<tr>
<th>Component</th>
<th>1986 Projection Effects from 1977 Base Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Usage decreased by 1.8% per year (16.2%)</td>
</tr>
<tr>
<td>Base Load Demand</td>
<td>Cooking reduced by 1%/yr.</td>
</tr>
<tr>
<td>Cooking Clothes Drying</td>
<td>Drying reduced by 1/2%/yr. (total 6 3/4%)</td>
</tr>
<tr>
<td>Domestic Hot Water</td>
<td>Reduced by 1 1/4%/yr.</td>
</tr>
<tr>
<td></td>
<td>(total 11 1/4%)</td>
</tr>
</tbody>
</table>

The 1986 electrical load profiles were developed by applying the projected energy reduction factors from Table D-1 to each of the corresponding components of the total electrical load for 1977. Profiles of the components of the average daily electrical load (exclusive of space conditioning) for 1986 are shown in Figure D-2. The annual total of each component is tabulated below:

<table>
<thead>
<tr>
<th>Component</th>
<th>Load, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseload</td>
<td>4641</td>
</tr>
<tr>
<td>Cooking and clothes drying</td>
<td>2070</td>
</tr>
<tr>
<td>Domestic hot water (average)</td>
<td>4384</td>
</tr>
</tbody>
</table>

Adjustment factors
- Phoenix = 0.88
- Albuquerque = 1.05
- Boston = 1.08
- Madison = 1.11

Space Conditioning Loads

Space heating and cooling loads for the residence were computed on an hourly basis using General Electric's Building Thermal Transient Load (BTTL) program. Program inputs included hourly weather and insolation data, building usage schedules, and a thermal model of the house. The thermal model was developed from the architectural plans and
analytically represented the significant heat flow paths, thermal capacitances, and heat generating elements of the house. The model assumed two thermostatically independent zones: one the living area; the other, the bedroom area. In winter, the living area thermostat was set at 20°C (68°F) during the day and at 17.2°C (63°F) at night; while the bedroom thermostat was maintained at 17.2°C (63°F) day and night. During the summer, the living and bedroom areas thermostats were set at 25.6°C (78°F) day and night.

Figure D-2. Average Daily Electrical Load Profile
The house was assumed to be occupied by a four-member family. The internal sensible and latent heat generated by occupants, lighting, cooking and miscellaneous appliances was derived from the hourly profiles of electrical loads and cooking loads established in the previous section. The latent portion of the load was estimated from any showers, boiling of water or other evaporative type processes occurring within the residence besides that due to human presence.

The infiltration rate through window and door leakage was assumed to be a function of wind speed. Since air flows are due to changes in air-stream static pressure, which, over the surfaces of buildings, are approximately proportional to the square of wind speed, the following equation was used in calculating infiltration gain of the building:

\[
\text{Infiltration} = 0.25 + 0.5 \times \left( \frac{\text{m/sec wind speed}}{13.41} \right)^2, \text{ air change per hour}
\]

The basic house model can also be adapted to assess the effect of an attached greenhouse and large south facing glass areas including doors. The south facing glass area for the basic house design was 7.8 m². For this passive house design, the south facing glass area was 53.9 m² (18.1 m² for the greenhouse, and 28 m² for the glass doors and 7.8 m² for glass area).

For a passive design house, the model includes a third zone for the attached greenhouse. In winter, the greenhouse thermostat was set to 32.2 °C (90 °F). The model assumed that when the greenhouse temperature exceeded 32.2 °C (90 °F) during the heating season, a blower would be activated to move the hot air in the greenhouse through ductwork either to outlets distributed throughout the living space, when a heat load existed; or to thermal storage, when no concurrent heat load existed. Night time heat loads were supplied from storage when stored energy was available. During the cooling season, venting of the greenhouse and shading of the south facing glass doors neutralized the threat of solar heat gain.

The resulting space conditioning loads predicted for the Boston residence by each model are shown below.
The effect of the greenhouse and the increased south facing glass area produced a reduction of 25.6% in annual heat load. The cooling load remained essentially unchanged, since the solar gain associated with the additional south facing windows and greenhouse were neutralized by shading and passive ventilation (open windows). The BTTL program predicted heat load reduction of 25.6% was compared with that predicted by the Passive Solar Handbook (Reference D-10) "rule of thumb." This rule related heat load reduction to the increase in south facing glazing and distinguishes between site locations and the use of night insulation on glazing. The heat load reduction "rule of thumb" is expressed as a correlation in Figure D-3 for Boston and Madison. The abscissa in this figure is evaluated by dividing the increased south facing window area by the floor area. The passive design house represents a net increase in south facing window area of 38.3 m². The floor area of the house is 148.7 m². This combination of increased south facing window area and floor area translate to a "rule of thumb" prediction of 23% reduction in heat load for Boston, which is about 10% below the prediction based on the BTTL results. Notice that the "rule of thumb" correlation also permits the evaluation of glazing with night insulation, which results in additional reductions in heat load. For the passive design house, the heat load reduction with night insulation increases from 23% to 58%. For this analysis, night insulation was assumed and the "rule of thumb" correlation was assumed; however, a conservative value of 48% for the heat load reduction was used in the hourly adjustment of the baseline heat load to yield an annual heat load of 5075 kWh.

For the design house in Madison, the passive solar heat load reduction amounted to 57% based on the "rule of thumb" correlation (see Figure D-3). As with the Boston house, a conservative value of 48% was used in the analysis for heat load reduction.
Figure D-3  Heat Reduction Due to South Facing Glazing

NOTES:
1. REFERENCE "PASSIVE SOLAR HANDBOOK"
Monthly space heating and cooling load profiles for the single family residence in Boston and Madison are listed in Table D-2. It is important to note that these space conditioning loads are loads which are satisfied by the heating and cooling equipment. In the all-electric house, the heat pump supplies these loads and creates an electrical demand equivalent to the space conditioning load divided by the heat pump COP. The monthly profiles of heat pump electrical requirements are shown in Figure D-3 for Boston and Madison. Both the space conditioning loads and the heat pump electrical requirements reflect the geographic differences between Boston and Madison, which are at the same latitude, but are 950 miles apart. Boston has higher cooling loads than Madison; however, Madison has the greater heating loads. The space conditioning demands are calculated hourly during the simulation and these plots provide the monthly summaries.
Table D-2
Northern Single Family Monthly Load Profiles

<table>
<thead>
<tr>
<th>MONTH</th>
<th>BOSTON (KWH)</th>
<th>MADISON (KWH)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COOLING</td>
<td>HEATING</td>
</tr>
<tr>
<td>JANUARY</td>
<td>0</td>
<td>1492</td>
</tr>
<tr>
<td>FEBRUARY</td>
<td>0</td>
<td>884</td>
</tr>
<tr>
<td>MARCH</td>
<td>0</td>
<td>785</td>
</tr>
<tr>
<td>APRIL</td>
<td>0</td>
<td>181</td>
</tr>
<tr>
<td>MAY</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JUNE</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>JULY</td>
<td>926</td>
<td>0</td>
</tr>
<tr>
<td>AUGUST</td>
<td>1077</td>
<td>0</td>
</tr>
<tr>
<td>SEPTEMBER</td>
<td>205</td>
<td>0</td>
</tr>
<tr>
<td>OCTOBER</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NOVEMBER</td>
<td>0</td>
<td>464</td>
</tr>
<tr>
<td>DECEMBER</td>
<td>0</td>
<td>1262</td>
</tr>
<tr>
<td>TOTAL</td>
<td>2148</td>
<td>5058</td>
</tr>
</tbody>
</table>
Figure D-3 Heat Pump System Electrical Requirements
For Northern Single Family Residence
APPENDIX E

ECONOMIC MODEL AND ASSUMPTIONS

ECONOMIC METHODOLOGY
APPENDIX E
ECONOMIC MODEL AND ASSUMPTIONS

Economic Methodology

Many of the simple investment evaluation techniques, such as payback time or simple return, suffer from two major drawbacks: life of the investment is not considered, and uneven costs and/or benefit streams cannot be handled.

The second item is of critical importance to alternate energy systems since virtually every economic scenario projects rising energy prices and therefore a steadily increasing benefit stream from an alternate energy system. For this reason, considerable effort has been made to stress "life cycle costing" for alternate energy systems. The following sections describe the life cycle costing model used in system sizing analysis.

Levelized Annual Cost

True life cycle cost analysis must necessarily consider the timing of costs and benefits as well as the magnitude. A method employed in previous General Electric solar and wind energy programs is to compare Levelized Annual Benefits (LAB), representing system energy savings, with the Levelized Annual Cost (LAC), the levelized dollar amount required to own, operate, and maintain a system during each year of the life of the system. Specifically, the levelized annual cost accounts for:

1. "Paying off" system capital costs (mortgage principal)
2. Paying mortgage interest
3. Paying property taxes and insurance

For cost evaluation and comparison of systems for future implementation, it is appropriate to express the levelized annual cost (LAC) referenced to a particular year, e.g., 1980. The result is the levelized annual cost in constant (base year) dollars given by:
\[
\text{LAC (constant ) } = \frac{\text{CRF'}}{\text{CRF}} \times \text{FCR} \times I + \text{AOC}
\]

where I is the capital cost of the solar system and AOC is the annual system operating cost which includes operation and maintenance and insurance. The parameter FCR is the fixed charge rate and represents the yearly cost of ownership, expressed as a percent of the capital cost, I. These costs consist of mortgage interest, principal and property taxes. The parameter CRF is the capital recovery factor, defined as the uniform periodic payment (as a fraction of the original principal) that will fully repay a loan (including all interest) in yearly periods over the loan lifetime at a specified yearly interest rate. The interest rate r used to calculate CRF is called the discount rate and for the homeowner is equal to the after-tax interest rate of the mortgage.

The relation expressing CRF as a function of r and system lifetime N is given as

\[
\text{CRF} = \frac{r(1+r)^N}{(1+r)^N - 1}
\]

The parameter CRF' is the corresponding capital recovery factor in constant (base year) dollars. CRF' is based on the real (or inflation adjusted) discount rate, r', defined as

\[
r' = \frac{1 + r}{1 + g} - 1
\]

where g is the general inflation rate. The equation for CRF also applies for CRF' with r' replacing r.

It should be noted that the LAC equation applies only to those systems without storage batteries since no replacement costs are necessary. For systems with storage, an addition term of the form

\[
\frac{\text{CRF'}}{(1 + r)^{11}} \times I' B
\]
must be added to account for the replacement of the battery in the eleventh year (e.g., for a battery life of 10 years). Here, $I_B$ is the cost of the replacement battery in constant 1980 dollars.

**Levelized Annual Benefits**

The comparison of the energy cost savings of the solar system to the levelized annual cost is accomplished by computing the levelized annual benefits (LAB) for the energy savings. LAB is inherently a function of present and projected energy prices and may be expressed by

$$\text{LAB (constant)} = \frac{\text{CRF}'}{\text{CRF}} \times M \times p_0 \times E_0$$

where $E_0$ represents the annual energy saved by the solar system, $M$ is an energy saving multiplier which is defined as the levelized value of an escalating cost stream which accounts for the rate of energy price escalation over the lifetime of the system, and $p_0$ is the energy price in year zero (for a 1986 start, year zero becomes 1985). For stand-alone systems, minimum monthly energy charges are included as a benefit in the computation of LAB.

The multiplier $M$ is a function of energy price escalation rate ($f$), system lifetime ($N$), and discount rate ($r$), and is expressed as

$$M = \frac{r(1 + f)}{r - f} \left[ \frac{(1 + r)^N - (1 + f)^N}{(1 + r)^N - 1} \right]^*$$

The energy price in year zero ($p_0$) is related to the energy price in constant (base year) dollars per energy unit ($p$) through the expression

$$p_0 = p \left( \frac{1 + f}{L + g} \right)^\Delta$$

where $\Delta$ is the number of years from the base year to year zero (value of 5 was used for a 1986 start with a base year of 1980).

*When $r=f$: $M=\text{CRF} \cdot N$
The economic viability of a system can be measured through the use of the cost-to-benefit ratio, which is defined as the ratio of the levelized annual cost to the levelized annual benefit. The system can be economically viable when the cost-to-benefit ratio is less than unity. The break-even system cost occurs when the ratio is exactly unity, i.e., when LAC and LAB are equal.

Economic Assumptions

This subsection spells out the basic assumptions that will be used in the economic analysis of PV residential systems. These assumptions concern the price of electricity in the designated regions for the 1986 time period and system capital cost. Also considered are assumptions regarding inflation, interest, and tax rates insofar as they will affect economic comparison results.

Model Assumptions

In order to utilize the cost-to-benefit ratio for system sizing studies, a set of economic assumptions were developed. These assumptions are summarized in Table E-1. Most of these assumptions are consistent with assumptions utilized in previous residential studies as Reference 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 cost-to-benefit ratio 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 per cent for a 20-year loan was assumed with a marginal income tax rate of 35 per cent for the homeowner. This is equivalent to a taxable income of approximately $25,000 at present tax rates. A 20-year life will be assumed for the solar systems of interest with a battery life of 10 years. Since several states and local communities have already exempted solar systems from property tax, no additional property tax will be assumed. These figures imply an annual cost or "fixed charge" of about 9.1% of the initial photovoltaic system cost. Annual operating costs are assumed to be $100/year for operation and maintenance and 0.5% of system cost.
Table E-1. Economic Assumptions for Optimization

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986 Start</td>
<td></td>
</tr>
<tr>
<td>General Inflation Rate:</td>
<td>5%</td>
</tr>
<tr>
<td>System Life:</td>
<td>20 Years</td>
</tr>
<tr>
<td>Insurance:</td>
<td>0.5% of Capital Cost</td>
</tr>
<tr>
<td>Electricity Price Escalation:</td>
<td>4% Over Inflation</td>
</tr>
<tr>
<td>Mortgage Rate:</td>
<td>10%</td>
</tr>
<tr>
<td>Battery Life:</td>
<td>10 Years</td>
</tr>
<tr>
<td>Tax Bracket:</td>
<td>35%</td>
</tr>
<tr>
<td>Albuquerque Electricity Price:</td>
<td>7.0¢/kWh</td>
</tr>
<tr>
<td>No Property Tax</td>
<td></td>
</tr>
</tbody>
</table>

for insurance. All components of the solar system are 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 1.

Capital Cost Estimates

To calculate the LAC, an estimate of the system capital cost is required. These cost estimates were made assuming 1986 price projections for equipment or 1986 National PV Program cost goals as for the array. In addition, estimates for installation costs and all remaining equipment costs were estimated as part of the balance of system costs. These latter values are only estimates made prior to final system design selection since the intent was to use these values in a relative comparison for system sizing and tradeoffs. The detailed design data within this report can now be used for obtaining detailed costs for installation and all small equipment costs. All the costs are in 1980$ and include in general, two 15% markups for distribution and contractors. These markups are probably low, but are used in this analysis until more detailed numbers are available for distribution networks.
The system capital costs were divided into an array cost, power conditioning cost, and balance of system costs. The balance of system costs were further separated into a fixed cost (i.e., however small a PV installation, a minimum amount of equipment, and thus, cost, is required independent of system size) and a variable cost based on system size. The variable, or area-related costs of a photovoltaic system include the cost of modules, array installation, and a portion of the power conditioning. The fixed costs obviously include the roof to load wiring, switchgear and power conditioning installation. There are other less obvious fixed costs, however.

For example, the cost of a power conditioning unit will include basic labor, cabinet and parts costs independent of size. In the area of operation and maintenance, a large fraction of the cost will not be area related. This would include almost all PCU and switchgear maintenance. For any given system, more or less fixed costs may be present, but the general contributors will remain.

The array cost assumed is 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, and remaining equipment costs. The array installation cost estimate was based on labor and material estimates from the 1978 Building Cost File Index for conventional asphalt shingle installation and increased by an assumed factor of 3 to account for the additional complexity of the PV shingle installation. The resulting cost is $35.35/m² per unit array installation.

Labor and material credit for weather tight replacement of the conventional shingles was then given at $12.29/m² for a net array installation cost of $23.06/m². These values are consistent with residential array installation cost estimates developed by Burt Hill Kosar Rittleman Associates, Reference 7, where non-optimized flat PV panel installation costs were approximately $40/m² and roof credits for integrated arrays were approximately $11/m².

The power conditioning subsystem cost estimates were based on cost projections from
several inverter manufacturers assuming high production levels in 1986 obtained from Reference 5. These projections were of the same magnitude as assumed in Reference 1 at $144/kVA in 1975 or $202/kVA in 1980. Several current cost quotes for the inverter, dc input filter and isolation transformer for 4, 8 and 10 kVA sized systems showed a fixed cost, independent of system size, and variable cost, dependent on system size. Based on this data, the $202/kVA cost for 1986 was separated into fixed and variable costs and then adjusted with two 15% markups resulting in a total PCS system cost estimate of $689 + $181/kVA.

The remaining fixed balance of system cost estimates include costs for junction boxes, disconnect switches, varistors, diodes, cabling and miscellaneous connectors, wire and tape and installation labor. Applying the markups resulted in a fixed cost of $1090. All of these system cost estimates are summarized in Table E-2. The costs listed in Table E-2 are basically direct system costs; however, imbedded in the assumed values are also the indirect costs associated with system design and installation. Some of the indirect costs could include architect fees, real estate fees, interest during construction, project management costs and the cost of the contingency and spares. It is difficult to accurately estimate all of these indirect costs and they are therefore included in general terms. The fixed costs associated with operation and maintenance for the system are not listed separately. These costs are normally added in the LAC calculation as a levelized annual value of $100/yr. This value relates back to a fixed capital cost of $1590 for the economic assumptions listed in Table E-1. No attempt was made to break out a fixed and variable portion of the operation and maintenance costs for this analysis.
Table E-2
Array Installation and Balance of System Costs

<table>
<thead>
<tr>
<th>SHINGLE ARRAY INSTALLATION ESTIMATES</th>
<th>1980$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor + Material</td>
<td>$35.35/m²</td>
</tr>
<tr>
<td>Credit for Conventional Shingles</td>
<td>$23.06/m²</td>
</tr>
</tbody>
</table>

**POWER CONDITIONING COSTS**

(Based on Projected High Production Estimates for 1986)
Includes Inverter, Input Filter and Transformer
Cost = $689 + $181/kVA
Or Approximately $689 + $15.60/m²
$689 + $15.60/m²

**B-O-P EQUIPMENT COST ESTIMATES**

(Includes Switches, Junction Boxes, Varistors, Busbar, Cabling)
$1090

**SUMMARY**

<table>
<thead>
<tr>
<th>ARRAY</th>
<th>$925/kWp</th>
</tr>
</thead>
<tbody>
<tr>
<td>VARIABLE COSTS</td>
<td>$38.66/m²</td>
</tr>
<tr>
<td>FIXED COSTS</td>
<td>$1779</td>
</tr>
</tbody>
</table>

**Energy Price Estimates**

Strong regional differences exist in energy pricing especially in electricity. In addition, the rates are changing very rapidly and it is difficult to continually obtain the most recent data. Since the first design for the Southwest was completed, a number of utilities were surveyed and provided updated average electrical energy prices for several regions (Reference 3). The updated values for Boston and Madison are 8.32¢/kWh and 5.32¢/kWh respectively. These values were used in the economic analysis.
APPENDIX F

RECTANGULAR PV SHINGLE MODULE CONSTRUCTION DETAILS
APPENDIX F
RECTANGULAR PV SHINGLE MODULE CONSTRUCTION DETAILS

The construction details of the rectangular shingle module are shown in Figure F-1, which is a section taken through the laminated assembly. A description of the construction follows.

![Diagram of Encapsulated Cell Subassembly](image)

**Figure F-1**

**Encapsulated Cell Subassembly**

The encapsulated cell subassembly, which is configured as a separately assembled component of the module, consists of the material stack-up shown in Figure F-1. A thermally tempered SUNADEX glass coverplate functions as the superstrate for the subassembly. The active circuit elements, including the solar cells and interconnectors, are sandwiched between layers of EVA/Craneglass which constitutes the encapsulant.

A rear side aluminum foil vapor barrier is used as a necessary design feature to increase the probability of survival under high humidity-freeze cycling environments. The EVA/Craneglass laminate provides the electrical isolation required between the active solar cell circuit components and this aluminum foil layer. The exposed outer layer of the aluminum foil is covered with Mead Sunstorm board, so no provisions are required to ground this foil. As depicted in Figure F-2, which is
an exploded view of this subassembly, the AMP flat conductor cable module-to-module interconnectors are installed as part of this subassembly and emerge from the laminate as flying leads which are routed through slits in the substrate. The copper conductor, which is equivalent to AWG12 in current carrying capacity, is covered on both sides with a polyester insulation layer with a rated operating voltage level of 300 V.
Module Assembly

The module assembly consists of the lamination of the encapsulated cell subassembly to the rear cover and to the substrate foam as shown pictorially in Figure F-3. The double-backed adhesive bonding strip is used to form the lap joint between the glass coverplate and substrate foam and to provide the salient during module installation to prevent the wind uplift forces from separating the installed shingle layers.

Figure F-3. Exploded View of Module Assembly
Mead Sunstorm board, which is a 2.0 mm thick weather-resistant solid fiberboard material, is used as the rear cover. This material is of a laminated construction with the core composed of highly sized reclaimed kraft fibers. All glue lines are bonded with waterproof PVA adhesive. Both outer facings of Sunstorm board are white—wet strength beached virgin kraft lining paper. This liner has a mold inhibitor added to reduce the possibility of mildew in exterior applications. Also, a clay coating is applied to facilitate high quality silk screen printing and various modes of paint application. The outer facings are secured to the core with a film of polyethylene. This film serves as a barrier, retarding water and moisture absorption, while giving added dimensional stability to the overall product. The outer skin is B.F. Goodrich reinforced Hypalon Flexseal which covers a closed-cell polyethylene foam to provide uniform thickness of the tub. Scotch-Crip Adhesive 4230 (3M Co.) is a contact cement used for the laminating adhesive for this assembly. It bonds the aluminum foil vapor barrier of the encapsulated cell subassembly to the rear cover and bonds the rear cover to the substrate foam. It is an economical, water-dispersed adhesive offering excellent wet strength, and resistance to temperatures as high as 163°C, and to high humidity and aging effects. This adhesive is applied with low pressure spray equipment, and produces no toxic or flammable noxious fumes.

The adhesive bonding strip is used to form the lap joint between the substrate foam and the glass coverplate and to bond and seal the overlapped joint between courses on the roof by bonding to the rear cover of the upper layer. A 3M Scotch-Mount double-coated tape #4008 is used for this application on the basis of its resistance to water absorption, and outdoor weathering involving a temperature range of -40 to 95°C with high humidity. This tape is applied to the outer surface of the substrate foam and glass coverplate leaving the liner in place on the exposed tape surface until such time as the overlapping shingle course is laid down.

Flat Conductor Cable Assemblies

Two flat conductor cable (FCC) assemblies, which are manufactured by AMP, Inc., are provided in each module. These FCC assemblies consist of a polyester insulated copper foil strip (equivalent to AWG 12) 16 mm (0.625 inch) wide by 0.13 mm (0.005 inch) thick, which have varying lengths depending on whether the assembly is to be
used as the positive or negative lead. The outer end of each FCC is terminated with a patented, crimp-type connector which was developed, and has been UL-approved, for under carpet ac power distribution systems. The stripped end of each FCC is soldered to the appropriate cell interconnectors to form the terminations for the module. Strain relief of these solder joints is provided by bonding to FCC within the substrate lamination between the rear core and the foam core.

**Module-to-Module Interconnects**

The electrical connection of the negative terminal of one module to the positive terminal of another module is accomplished through crimp connections of the splice terminals to a common FCC carrier.
DISTRIBUTION:

TID-4500-R66, UC-63a (224)

L. A. Barrett (25)
Department of Energy
Division of Photovoltaic Energy Systems
Forrestal Bldg.
1000 Independence Ave. SW
Washington, DC 20585
Attn: M. B. Prince
V. Rice
A. Krantz

Department of Energy
Division of Active Heating and Cooling
Office of Solar Applications for Bldgs.
Washington, DC 20585
Attn: Robert D. Jordan, Director

Department of Energy
Division of Passive and Hybrid
Office of Solar Applications
Washington, DC 20585
Attn: Michael D. Maybaum, Director

Jet Propulsion Laboratory (15)
4800 Oak Grove Drive
Pasadena, CA 91103
Attn: R. V. Powell (4)
R. Ferber
K. Volkmer
W. Callaghan
R. Ross
R. S. Sugimura
R. Weaver
S. Krauthamer
A. Lawson

Jet Propulsion Laboratory
Solar Data Center
MS 502-414
4800 Oak Grove Drive
Pasadena, CA 91103

R. Tlubors (2)
MIT-Energy Laboratory
E40, 172
Cambridge, MA 02139

Solar Energy Research Institute (6)
1536 Cole Boulevard
Golden, CO 80401
Attn: D. Feucht
S. Silliman
T. Basso
M. DeAngelis
G. Nuss
R. DeBlasio

SERI, Library (2)
1536 Cole Boulevard, Bldg. #4
Golden, CO 80401

SERI
Mail Stop 15-3
1617 Cole Blvd.
Golden, CO 80401

NASA Lewis Research Center
21000 Brookpark Laboratory
Cleveland, OH 44135

Florida Solar Energy Center
300 State Road 401
Cape Canaveral, FL 32920
Attn: S. Chandra

EPRI (3)
P.O. Box 10412
Palo Alto, CA 94303
Attn: Frank Goodman
Edgar Demeo
Roger Taylor

House Science and Technology Committee
Room 374-B
Rayburn Building
Washington, DC 20515
Attn: Don Teague

MIT-Lincoln Laboratory (6)
P.O. Box 73
Lexington, MA 02173
Attn: M. Pope
M. Russell (2)
E. Kern (3)
David Jay Feinberg Architect  
Attn: David Feinberg, AIA  
Suite 302  
10700 Caribbean Blvd.  
Miami, FL 33189  

David L. Smith Architect  
Attn: David L. Smith  
505 Hamilton Street  
Schenectady, NY 12305  

David Wong & Associates  
Attn: David Wong, P.E.  
American Security Bank Bldg.  
1314 S. King St., Suite 1461  
Honolulu, HI 96814  

Dayton Power & Light Co.  
Attn: Bruce Curtis  
P.O. Box 1247  
Dayton, OH 45401  

Denny Long  
Route 1 Box 158  
Woodland, CA 95695  

Design Direction  
Attn: Dennis John Becker, AIA  
1588 Tanglebriar  
Fayetteville, AR 72701  

Dick Jenkins, Vice President  
Product Development  
10221 Wincoplin Circle  
Columbia, MD 21044  

Dick Lamar Architect  
Attn: Dick Lamar, AIA  
201 Woodrow Street  
Columbia, SC 29205  

Donald F. Monell Architect  
Attn: Donald F. Monell, AIA  
11 Pleasant Street  
Gloucester, MA 01930  

Donald M. Watts Architect  
Attn: Donald M. Watts  
1649 Huntington Drive  
South Pasadena, CA 91030  

Donald Watson Architect  
Attn: Donald Watson, AIA  
P.O. Box 401  
Guilford, CT 06437  

Downing Leach & Associates  
Attn: Jim Leach  
3985 Wonderland Hill Avenue  
Boulder, CO 80302  

Dr. Stephen K. Young  
(10) SAI  
1710 Goodridge Drive  
McLean, VA 22102  

Dublin Bloom Associates  
Attn: H. Robert Sparkes, P.E.  
312 Park Road  
West Hartford, CT 06107  

Dyer and Watson Architects  
Attn: James Watson  
24100 Chagrin Blvd.  
Cleveland, OH 44122  

EAI Inc.  
Attn: Dr. Jerry Alcone  
13300 Hugh Graham Rd., NE  
Albuquerque, NM 87111  

Earth Dynamics  
Attn: Peter Slack  
P.O. Box 1175  
Boulder, CO 80002  

Earthworks  
Attn: Steven E. Golubski  
20 West 9th Street  
Kansas City, MO 64105  

Edwards & Daniels Associates  
Attn: A. Brett Bullock  
525 E. 300 S  
Salt Lake City, UT 84102  

Ekosca  
Attn: Lee Porter Butler  
573 Mission Street  
San Francisco, CA 94105  

Ellerbe Associates, Inc.  
Attn: Jim Gelfer  
Manager of Professional Services  
Electrical Design Department  
One Apple Tree Square  
Bloomington, MN 55420  

Ellmore/Titus/Architects/Inc.  
Attn: S. A. Titus, AIA  
736 Chestnut Street  
Santa Cruz, CA 95060  

Dist-5
Fred W. Forbes & Associates, Inc., Architects AIA and Engineers NSPE
P.O. Box 443
Xenia, OH 45385

Galliher Schoenhardt & Bailer
Attn: Robert P. Morcarsky
The Courtyard No. 10
Simsbury, CT 06070

Gary Copeland
31-81 Poplar Avenue
Memphis, TN 38111

Gary Marcniak
6582 N. 90th
Milwaukee, WI 53224

Gelger Borger & Associates
Attn: Karl Beltln, PE
500 Fifth Avenue
New York, NY 10036

General Electric Co.,
Attn: E. M. Mehallick
Advanced Energy Programs
P.O. Box 8661
Philadelphia, PA 19101

Gensler Architects, Inc.,
Attn: James L. Gensler, AIA
819 N. Marshall Street
Milwaukee, WI 53202

George A. Roman & Associates, Inc.,
Attn: George A. Roman, AIA
One Gateway Center
Newton, MA 02158

Georgia Institute of Technology
Attn: Richard Williams
College of Engineering
Atlanta, GA 30332

Georgia Institute of Technology
Engineering Exp. Station
Attn: Joan Wood
225 North Avenue, NW
Atlanta, GA 30332

Georgia Power Company
Attn: Gary Birdwell
P.O. Box 4545
Atlanta, GA 30303

Gerken & Upham Architects, Inc.,
Attn: Mr. Carl Gerken
P.O. Box 155
Ormond Beach, FL 32074

GK Associates
Attn: Draw Gillette
319 Holbrook Road
Bedford, NH 03102

Glass Energy Electronics
Attn: Ron Wilson
4463 Woodland
Park Avenue North
Seattle, WA 98103

Graham Hubenthal
Box 777
Soap Lake, WA 98851

Greenles/Reese Associates, Ltd.,
Attn: Frank L. Reese, AIA
6400 Flying Cloud Drive
Suite 210
Eden Prairie, MN 55344

Gribbell/Gorondona/Savoye
Attn: Michael D. Cortner
2352 Metairie Road
Metairie, LA 70001

Gunnar, Birkerts & Associates
Attn: Charles Eleckenstein
292 Harmon Street
Birmingham, MI 48009

H. L. Youngkln AIA Architect
Attn: Harry Younkin, AIA
1202 E. Maryland Avenue
Phoenix, AZ 85014

Hahn Jackson Lloyd Thresher Arch., & Eng.
Attn: Timothy A. Henning, AIA
Top Hat Road
Princeton, IN 47670

Hankins & Anderson, Inc.
Attn: H. C. Yu
1680 Santa Rosa
Richmond, VA 23288

Harthorne Hagen Gross AIA & Assoc.
Attn: Clifford Gross, AIA
220 Marina Mart 1500 Westlake N.
Seattle, WA 98109
Johnstown Architects, Inc.
Attn: Benjamin J. Policicchio, AIA
GKI Building
777 Goucher Street
Johnstown, PA 15905

Jones & Mayer
Attn: Charles Mayer
13100 Manchester Road
St. Louis, MO 63131

Jones & Strange-Boston Ross Building
Attn: Donald L. Strange-Boston, AIA, PE
Main Street at 8th
Richmond, VA 23219

Joseph J. Del Clotto, Jr., Architect
Attn: Joseph Del Clotto, AIA
201 Church Road
Lansdale, PA 19446

JSR Associates
Attn: Dr. John S. Reuyl
2280 Hanover Street
Palo Alto, CA 94306

Kammeraad Stroop van der Leek
Attn: Paul van der Leek
355 Settlers Road
Holland, MI 49423

Keith Vaughan Associates
Attn: Keith Vaughan
3136 E. Madison Street
Seattle, WA 98112

Kelbaugh and Lee Architects
Attn: Douglas Kelbaugh, AIA
240 Nassau
Princeton, NJ 08540

Kitchen & Associates
Attn: Deborah K. Gawthrop
Office Manager
Box 935
Philadelphia, PA 19105

Knoell/Quidort Architects
Attn: Hugh Knoell, Jr., AIA
1131 East Highland
Phoenix, AZ 85014

Korsunsky Krank Erickson Architects
Attn: Daryl P. Fortier, AIA
Director of Design
570 Galaxy Building
330 Second Avenue South
Minneapolis, MN 55401

Kruger Kruger Albenberg
Attn: Kenneth Kruger
2 Central Square
Cambridge, MA 02139

Lancaster and Lancaster Architects
Attn: Earl M. Lancaster, AIA
P.O. Box 10
Auburn, AL 36830

Lane & Associates Architects
Attn: John E. Lane, AIA
1318 North B Street
P.O. Box 3929
Fort Smith, AR 72913

Lapicki/Smith Associates
Attn: Carol A. Moore
617 Park Avenue
Baltimore, MD 21201

Lee R. Connell Architect, Inc.
Attn: Lee R. Connell, Jr., AIA
2500 Joseph Street
New Orleans, LA 70115

Leo A. Daly
Attn: Arturo Bantog
1025 Connecticut Ave., NW
Suite 712
Washington, DC 20036

Leon Diller
911 22nd Street
Santa Monica, CA 90403

Leonard Winberg, AIA
160 Hillfair Circle
White Plains, NY 10605

Living Systems
Attn: Jonathan Hammond
Route 1 Box 170
Winters, CA 95616
Londe Parker Michels Consultants
Attn: Timothy I. Michels
7438 Forsyth
Suite 202
St. Louis, MO 63105

Long Hoeft Architects
Attn: Mr. Gary Long, AIA
1228 Fifteenth Street, Suite 401
Denver, CO 80202

Louisiana Institute of Building Sciences
Attn: Richard C. Thevenot
830 North Street
Baton Rouge, LA 70802

Lydia Straus-Edwards Arch. Designer
Attn: Lydia Straus-Edwards
331 Main Street South
Woodbury, CT 06798

M. David Egan, PE
P.O. Box 365
Anderson, SC 29621

Manuel Perez
1056 Hunting Lodge Drive
Miami Springs, FL 33166

Marcel E. Sammut Arch. & Struct. Eng.
Attn: Marcel E. Sammut, AIA
30 Anthony Circle
Newtonville, MA 02160

Mark Beck Associates
Attn: Peter Powell, AIA
762 Fairmount Avenue
Towson, MD 21204

Marlin H. Andersen Homes
Attn: Marlin Grant, President
8901 Lyndale Avenue South
Bloomington, MN 55420

Martin Marlette Corp.
Attn: M. S. Imanura
P.O. Box 179
Denver, CO 80201

Mass Design
Attn: Gordon Tully
138 Mt. Auburn St.
Cambridge, MA 02138

Massachusetts Institute of Technology
Attn: Tim Johnson
Department of Architecture
Cambridge, MA 02139

Matrix Inc.
Attn: Edward Mazria
400 San Felipe NW
Suite 6
P.O. Box 4893
Albuquerque, NM 87106

Mayhew Homes Corp.
Attn: John Odegard
P.O. Box 1778
Gainesville, GA 30501

McCleer Architect
Attn: Mike McCleer
2249 First National Bldg.
Detroit, MI 48226

MCM
Attn: Michael C. Merchant
P.O. Box 7707
Stanford, CA 94305

Merriman, Deasy & Whisenant, Inc.
Attn: Bruce D. Fraser, AIA
979 Osos Street
Suite C
San Luis Obispo, CA 93401

Metcalf and Associates
Attn: Susan Shaw
3222 N Street NW
Washington, DC 20007

Miami University of Ohio
Attn: Fuller Moore
Department of Arch.
Oxford, OH 45056

Michael Albanes
2368 Cherry Street
Denver, CO 80207

Michael Lesburg Architect
Attn: Michael Lesburg, AIA
1430 Massachusetts Avenue
Cambridge, MA 02138

Miller Hanser Westerbeck Bell Architects, Inc.
Attn: Jay Johnson
Suite 300 Butler Square
100 N 6th Street
Minneapolis, MN 55403
Perez & Hurtado Architects, Inc.
Attn: Jess F. Perez
850 E. Chapman Avenue
Suite A
Orange, CA 92666

Perkins & Will
Attn: Bill Bobenhausen
445 Hamilton Avenue
White Plains, NY 10601

Peter D. Paul, AIA
P.O. Box 271
50 Galesil Drive
Wayne, NJ 07470

Peter Dobrovolny, AIA
Box 133
Old Snowmass, CO 81654

Peter Van Deesser
634 Garcia Street
Santa Fe, NM 87501

Peterson Construction Company
Attn: Robert Peterson, President
6100 S. 14th Street
Lincoln, NE 68512

Pettit & Bullinger Architects
Attn: Hell C. Pettit, AIA
P.O. Box 2726
1202 East First
Wichita, KS 67201

Phillip West, Donald Bergstrom & Assoc.
Attn: Edward J. Mercyn, AIA
33 East First Street
Hinsdale, IL 60521

Phineas Alpers Architects, Inc.
Attn: Phineas Alpers, AIA
344 Newbury Street
Boston, MA 02115

Potomac Energy Group
Attn: David Johnston
401 Wythe Street
Alexandria, VA 22314

Price and Partners
7301 Birch Avenue
Takoma Park, MD 20012

Price Roth & Muse Architects
Attn: William Price
P.O. Box 1014
Tri-City Airport
Blountville, TN 37617

Princeton Energy Group
Attn: Harrison Fraker, AIA
729 Alexander Road
Princeton, NJ 08540

RA Solar Consultants, Inc.
Attn: Harry E. Burns, Jr., AIA
Park 20 West
Blountstown Highway
Tallahassee, FL 32304

Ralph E. Klene & Associates
Attn: Ralph E. Klene, AIA
1006 Grand Avenue
Kansas City, MO 64106

Ralph Jefferson, AIA Architect
497 Springfield Avenue
Summit, NJ 07901

Ramon Zambrano & Associates
Attn: Dan Holland
1015 Battery Street
San Francisco, CA 94111

Rasmussen Hobbs Architects/Planners
Attn: D. L. Hobbs, AIA
#9 Saint Helens
The Henry Drum House
Tacoma, WA 98402

Raymond E. Phillips, Architect
Attn: Raymond E. Phillips, AIA
703 SW McKinley
Des Moines, IA 50315

Raymond J. Bahm
2513 Kimberley Ct. NW
Albuquerque, NM 87120

Reyn Hendrickson
4480 Grand River Street
Novi, MI 48050

Richard Schwarz/Nell Weber
Attn: Nell Weber, AIA
3601 Park Center Boulevard
Minneapolis, MN 55416
Smith, Hinchman, and Grylls
Attn: Randal E. Swelch
455 West Fort Street
Detroit, MI 48226

Steelcraft Corporation
Attn: Gary Ford
Box 12408
Memphis, TN 38112

Sol Tec
Attn: Jim Crouch
2160 Clay Street
Denver, CO 80211

Sunpower Industries of Kent
Attn: Al Abramson
10837 86th SE 200th
Kent, WA 98031

Solar Building Corp.
Attn: John Newman
1004 Allen
St. Louis, MO 63104

Sunrise Builders
Attn: Rich Schwoisky
P.O. Box 125
Grafton, VT 05146

Solar Design Associates
Attn: Steven J. Strong
Conant Road
Lincoln, MA 01773

Sverdrup and Parcel Eng & Arch
Attn: Frank Kessler
1650 W. Alameda Drive
Tempe, AZ 85282

Solar Environmental Engineering
Attn: Dave Gunther
2524 East Vine Drive
Fort Collins, CO 80524

Tackett Way Lodholz
Attn: George Way
3121 Buffalo Speedway
Suite 400
Houston, TX 77098

Solar Processes Inc.
Attn: Gordon Preiss
11 Velvet Lane
Mystic, CT 06355

Talbot & Associates
Attn: Thomas L. Ainscough, AIA
P.O. Box 2224
Virginia Beach, VA 23452

Solar Technology Systems
Attn: Charles Orr
81A Upper St. Giles St.
Norwich, ENGLAND NR21AB

Texas Tech University
Attn: Professor Carl Childers
Division of Architecture
Box 4140
Lubbock, TX 79409

Solar Arc
Attn: Anthony Quirl
2040 Addison Street
Berkeley, CA 92704

The Architects Collaborative
Attn: Ms. Gail Flynn
48 Brattle Street
Cambridge, MA 02138

Solararex Corporation
Attn: Marth Bozman
1335 Piccard Drive
Rockville, MD 20850

The Architects Taos
Attn: William Mingenbach
Box 1884
Taos, NM 87571

South Street Design
Attn: Don Prowier
2233 Grays Ferry Avenue
Philadelphia, PA 19146

The Architectural Alliance
Attn: Peter Pflister, AIA
400 Clifton Avenue
Minneapolis, MN 55403

Southern Solar Energy Center
Attn: S.C. Nelson
61 Perimeter Park
Atlanta, GA 30341

The Burns/Peters Group
Attn: William L. Burns, AIA
8000 Pennsylvania Circle NE
Albuquerque, NM 87110
Warehouse Specialist, Inc.
Attn: Mark van Deyoclat
655 Brighton Beach Road
Menasha, WI 54952

Werner Burns Toan Lunde
Attn: Fritz Lunde
330 W. 42nd Street
New York, NY 10036

WED Enterprises
Attn: Mike McCullough
1401 Flowers Street
Glendale, CA 91201

Wendell H. Lovett Architect
Attn: Wendell H. Lovett, FAIA
2134 Third Avenue
Seattle, WA 98121

William Drevo Architect
Attn: William Drevo, AIA
6125 29th Street, NW
Washington, DC 20015

William J. Bates Architect
Attn: William J. Bates, AIA
57 Martin Drive West
Pittsburgh, PA 15216

William Morgan Architect
Attn: Thomas A. McCrory, AIA
220 East Forsyth Street
Jacksonville, FL 32202

William Tao & Associates
Attn: Richard Janus
2357 59th Street
St. Louis, MO 63110

William Thomas Meyer, AIA
Attn: William T. Meyer
353 East 72nd Street
New York, NY 10021

Wright, Pierce, Eng. & Arch.
Attn: Douglas Wilkie
38 Roosevelt Avenue
Glen Head, NY 11545

Wright-Pierce Associates & Eng.
Attn: Barbara Freeman
99 Main Street
Topsham, ME 04086

ZOEworks
Attn: Garth Collier, AIA
70 Zoe Street
San Francisco, CA 94107

Zomeworks Inc.
Attn: Steve Beer
P.O. Box 712
Albuquerque, NM 87103