Residential Design
Sensitivity Analysis

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RESIDENTIAL DESIGN SENSITIVITY ANALYSIS

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ABSTRACT

This report presents the results of a study to identify the effect passive solar heating strategies will have on residential photovoltaic (PV) system performance in 1986. In addition, previous design and analysis studies conducted by General Electric and Westinghouse were evaluated to determine whether passive heating would significantly alter their results.

Passive heating contributions were found to reduce interaction of the PV system with the load. However, the differences in displaced utility electricity between small and large passive contributions are small. These results show the relative insensitivity of PV system performance to large amounts of passive solar heating. Once daytime heating has been achieved through suntempering, any further passive contribution has minimal effect on daytime electrical heating loads. Incorporation of passive heating systems in a residence does not affect the definition of optimum PV system size.

The prototypes developed by GE and Westinghouse were found equivalent to energy conserving 1986 residences with suntempering. Since passive heating savings beyond that required for suntempering do not affect PV system performance, incorporation of larger passive savings in these prototypes will have no effect on their previously reported performance.

ACKNOWLEDGEMENTS

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Several individuals contributed to this project. Alexander Shaw, III, conducted many of the passive and conventional space conditioning load simulations. Paul McClure and Mary Murphey provided editorial support. Paula Knott produced the final manuscript.
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SECTION 1.0

SUMMARY

1.1 Introduction

This report presents the results of a study on residences that incorporate both passive solar heating strategies and photovoltaic (PV) arrays for electrical power generation. The study was conducted between August 1980 and January 1981. This section summarizes the selection of case study locations, determination of residential load characteristics, solar system definition, performance analyses results and study conclusions.

The objectives of this study were to identify how marketable passive technologies for space conditioning will affect residential power loads and the effect this may have on residential PV system design in 1986. An additional objective was to evaluate the sensitivity of previous residential PV design and analysis study results to the use of passive solar strategies. Analyses in this study were based on estimates of energy consumption by all-electric residences in the mid-1980s and performance estimates of utility-interactive PV systems without storage. These analyses were conducted on a regional, case-study basis to reflect significant climatic differences.

1.2 Case Study Selection

Three case study site locations were considered to represent systems performance in the Southwest, Northeast and Southeast regions of the country. These sites were Phoenix, Boston and Nashville. The following selection criteria were defined for case study site locations: the site should represent the dominant weather conditions of the region; the site must have been considered in previous residential PV design and analysis studies; and hourly meteorological data must have been recorded for the site.

Parameters used to identify the case study locations included insolation, temperature, relative humidity, and wind velocity obtained from records of local climatic data. Hourly weather data were obtained from the National Climatic Center.
1.3 Residential Load Characteristics

Residential loads were based on the living patterns for an average size family of 4-5 members in single family detached housing expected for the middle-income mass market. Loads for base appliances, domestic water heating and space conditioning were projected for 1986 using estimates of energy conservation applied to 1978 levels. In the 1978 and 1986 mean annual loads listed in Table 1-1 for an all-electric non-solar residence, heating and cooling loads are shown for a 139.4 m² (1500 ft²) floor area.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>APPLIANCES</th>
<th>DHW</th>
<th>HEATING</th>
<th>COOLING</th>
<th>TOTAL</th>
</tr>
</thead>
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<tr>
<td>BOSTON</td>
<td>7520 6844</td>
<td>5348 4813</td>
<td>8066 4033</td>
<td>1010 505</td>
<td>21944 16195</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>7520 6844</td>
<td>4457 4011</td>
<td>4537 2269</td>
<td>4867 2434</td>
<td>21381 15558</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>7520 6844</td>
<td>4099 3689</td>
<td>1712 856</td>
<td>5409 2705</td>
<td>18740 14094</td>
</tr>
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</table>

Mean annual loads for non-solar residences in the mid-1980s are estimated to be an average of 33% less than 1978 loads for the case study cities. These levels of energy conservation include a 9% reduction in base appliance loads and a 10% reduction in domestic water heating loads. However, the largest reductions are expected in space conditioning loads. Heating and cooling loads are expected to be 50% of those in 1978.

Space conditioning demand in 1978 and 1986 Boston, Nashville and Phoenix residences were scaled from a normal distribution of heating and cooling performance developed from survey data. Heating and cooling performance of the GE and Westinghouse prototypes are shown with mean, 20th and 80th percentiles of this distribution in Table 1-2. These values were normalized for differences in residence size and weather data to facilitate comparison.
TABLE 1-2. COMPARISON OF HEATING AND COOLING DEMANDS (kWh/DDc-m²)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEMAND</th>
<th>1978 RESIDENCES</th>
<th>1986 RESIDENCES</th>
<th>PROTOTYPES</th>
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<tr>
<td></td>
<td></td>
<td>20th</td>
<td>MEAN</td>
<td>80th</td>
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<tr>
<td>BOSTON</td>
<td>HEATING</td>
<td>.045</td>
<td>.058</td>
<td>.069</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.043</td>
<td>.052</td>
<td>.060</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>HEATING</td>
<td>.040</td>
<td>.051</td>
<td>.060</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.030</td>
<td>.037</td>
<td>.057</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>HEATING</td>
<td>.029</td>
<td>.048</td>
<td>.066</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.031</td>
<td>.035</td>
<td>.039</td>
</tr>
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</table>

In all cases, the prototypes show lower heating demand than expected for the average 1986 residence. In most cases, the prototypes show lower heating demand than expected for more than 80% of the residences. The prototype heating demands reflect their use of more insulation, and infiltration reductions. The prototypes show higher cooling demands than expected for the average 1986 residence. The cooling demands reflect their use of more south-facing glazing than generally employed. Despite these differences, the seasonally weighted annual values for the prototypes adequately exhibit demands expected for 1986 residences.

1.4 Solar Energy Systems Definition

For all sites, a set of standard parameters was used to define each passive heating and PV power system. Direct gain, glazed masonry wall, and sunspace passive heating systems were evaluated for each site. The PV system in all cases was defined as a utility-interactive, flat-plate passively-cooled, PV-only system without storage. Solar domestic hot water system options were not considered.
Reference characteristics of the passive heating systems were based upon the following collection and storage parameters. Vertical south-facing double-glazing was assigned a transmissivity of 0.747 at normal incidence. The capacity of directly irradiated thermal storage was defined as 0.17 kWh/C·M² (30 BTU/F·FT²) of collection aperture area. The rate of radiant thermal transfer was assumed as 0.006 kW/C·M² (1.0 BTU/hr·F·FT²) of exposed surface area.

Reference characteristics of the PV system were based upon the following array and power conditioning parameters. Encapsulated cell efficiency used in the analysis was 13.5% at 28°C and 1 kW/M² insolation. A nominal operating cell temperature (NOCT) of 60°C was assumed. An array packing density of 0.87 was used in all cases. Inverter efficiency was assumed to be 0.9.

1.5 Performance Analyses

Performance of passive and utility-interactive PV systems without storage was simulated for 1978 and 1986 residences in Boston, Nashville and Phoenix. Two ranges of passive contribution were simulated to examine heating demand reductions less than 30% and more than 60% in each city. Utility interactive PV systems without storage were simulated using 50 m² and 90 m² array areas. Nomographs were prepared to expand the applicability of data from these points over a broad range of annual daytime loads and array areas for each city.

The 1986 heating demand (MWh/yr) and heating electrical load (MWh/yr) for an average 139.4 m² (1500 ft²) residence in Boston, Nashville and Phoenix is shown in Table 1-3. Similar to results (1) for an average 1978 residence, increasing the amount of passive savings in heating demand from under 30% to more than 60% reduced the daily (24 hr.) heating load by more than half, and reduced the daytime heating load by one-half to three-fourths.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SOLAR PCT.</th>
<th>HTG. DEMAND</th>
<th>HTG. ELEC. LOAD</th>
<th>TOTAL ELEC. LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>BLDG. AUX.</td>
<td>DAILY</td>
<td>DAILY DAYTIME</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOSTON</td>
<td>27.5</td>
<td>12.63 9.15</td>
<td>2.90 0.69</td>
<td>14.79 8.04</td>
</tr>
<tr>
<td></td>
<td>64.7</td>
<td>12.63 4.46</td>
<td>1.39 0.23</td>
<td>13.31 7.59</td>
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<td>NASHVILLE</td>
<td>28.1</td>
<td>7.30 5.25</td>
<td>1.61 0.35</td>
<td>12.75 7.15</td>
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<tr>
<td></td>
<td>70.4</td>
<td>7.30 2.16</td>
<td>0.66 0.08</td>
<td>11.78 6.80</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>28.4</td>
<td>2.89 2.07</td>
<td>0.61 0.09</td>
<td>11.71 6.95</td>
</tr>
<tr>
<td></td>
<td>65.4</td>
<td>2.89 1.00</td>
<td>0.29 0.04</td>
<td>11.39 6.90</td>
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1-4
The annual performance (MWH/yr) of utility energy displaced and sellback energy from a 50 m² array PV system for a 139.4 m² residence in 1986 is shown in Table 1-4. Results for the two ranges of passive heating savings show that passive heating contributions reduce interaction of the PV system with the load. PV system/on-site load interaction is reduced by 7% in Boston and 2% in Nashville for the increase in passive savings shown. No significant change occurs in Phoenix due to the heating load's minor contribution to the total load.

### TABLE 1-4. ANNUAL PERFORMANCE (MWh/yr) OF A 50 M² ARRAY PV SYSTEM IN 1986

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>UNDER 30% PASSIVE SAVINGS</th>
<th>OVER 60% PASSIVE SAVINGS</th>
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<td>ELEC. LOAD TOT</td>
<td>DAY DIRECT SOLD</td>
</tr>
<tr>
<td>BOSTON</td>
<td>14.79 8.04</td>
<td>4.09 1.82</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>12.75 7.15</td>
<td>4.03 3.10</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>11.71 6.95</td>
<td>4.46 5.22</td>
</tr>
</tbody>
</table>

Small differences in displaced utility electricity and PV system output sold at the under-30% and over-60% level of passive contribution indicate the PV system's relative insensitivity to large amounts of passive solar heating. Once daytime heating has been achieved through suntempering, any further passive contribution will have minimal affect upon total daytime electrical loads.

Load and system performance values shown for the 1986 residences with less than a 30% passive contribution are equivalent to those for prototypes developed by GE and Westinghouse, once weather conditions, residence size, and system efficiency are normalized. This data indicates that even if the prototypes had been developed with more than 60% passive heating contribution, no significant differences from performance predictions previously reported would occur.

1.6 Conclusions

Passive heating contributions in all-electric residences reduce utility electricity displacement by a utility-interactive PV system without storage. However, the small reduction in PV system/load interaction shows that the PV system's performance is relatively insensitive to large amounts of
passive solar heating. This is due to the fact that the PV system does not see the various electrical loads from appliances, DHW or heating separately, but only as total electrical load. When daytime heating has been achieved through suntempering (30% passive contribution) daytime electrical heating demand drops to a minimal portion of the total electric load. It follows that further reductions of the electrical heating load (i.e., increasing passive contribution) would have minimal impact upon PV system interaction.

The prototypes developed by GE and Westinghouse were found equivalent to 1986 energy conserving residences with suntempering. The prototypes space heating demands were found to be lower than expected for average 1986 residences in Boston, Nashville and Phoenix. In most cases, the prototypes show lower heating demand than expected in more than 80% of the 1986 residences. Increasing the amount of passive heating savings in the prototypes will not affect their previously reported PV system performance.

Since PV system performance is relatively insensitive to large amounts of passive contribution, passive incorporation in a residence does not affect the definition of optimum PV system size.
SECTION 2.0

INTRODUCTION

Several studies (2,3,4) have concluded that residential photovoltaic (PV) applications will be one of the earliest and largest markets for PV commercialization in 1986. Further investigations have addressed the conceptual design of residential PV systems on a regional basis. Although passive solar strategies to reduce space conditioning loads have been considered in these regionally specific studies, there has been no systematic evaluation of any passive solar effects on the design or operation of the PV systems.

The AIA Research Corporation was asked to investigate the impact of passive solar space conditioning strategies and evaluate whether their effect would significantly alter the results of previous design and analysis studies. Selection of one solar technology versus another on the basis of marginal costs or benefits was beyond the scope of this study, as was the design of an integrated passive and PV system.

The investigation focused on all-electric single-family detached residences with passive heating and interactive PV systems in the Southwest, Northeast, and Southeast sections of the United States. Performance characteristics of the residences, passive systems, and PV systems were projected for marketable homes in the 1986 time-frame.

Three case study locations, Phoenix, Boston, and Nashville, were selected as representative of the three regions. Residential energy consumption characteristics for the mid-1980s were developed for space conditioning, domestic hot water, and base appliance loads using projections from 1978 baseline data. The residences were modified to incorporate direct, indirect, and isolated gain passive systems appropriate for the 1986 market.

System output for indexed areas of a utility-interactive, flat-plate air-cooled PV array were determined for each study site. Loads for the residences were determined for conventional stand-alone heat pump heating as well as indexed savings in auxiliary heating requirements from each type of passive system. Performance and economic effects of the passive contribution on the PV system were evaluated for parameter changes in each passive system. PV system operation was correlated with the amount of passive heating contribution. A block diagram of the study sequence is shown in Figure 2-1.
SECTION 3.0  
CASE STUDY SELECTION

3.1 Summary

Phoenix, AZ; Boston, MA; and Nashville, TN, were selected as case study site locations to represent PV and passive system performance in the three regions of the U.S. previously identified (3,4) as having significant potential PV system use—the Southwest, Northeast, and Southeast. Objectives for the selection of case study locations were three-fold. First, the sites should be representative of economic conditions in the regions. Next, the sites should allow a nominal representation of climatic conditions and expected PV and passive system performance throughout the regions. Finally, the sites should be documented by sufficient historical weather data to allow interpolation for microclimatic variations once climate-dependent performance principles were identified.

Climatic parameters used to identify the candidate case study locations included hourly insolation, temperature, relative humidity, and wind velocity. This data was taken from Typical Meteorological Year (TMY) magnetic tape records.

Weather data from previous research (3.4) on PV performance at the three case study locations was compared with the TMY weather data; variations among the different data sets were generally less than 10%.

3.2 Regional Definition

Previous conceptual design and analysis studies of residential PV systems (3,4) have identified the Southwest, Northeast, and Southeast regions of the U.S. as areas of significant potential PV system use. This is based on abundant incident solar radiation in the Southwest; extensive use of electricity at high energy costs in the Northeast; and the correlation of peak summer loads and PV system output in the Southeast.
In previous energy studies (1,5,6) conducted by the AIA/RC, several major climatic region classification methods were evaluated and ranked on the basis of such criteria as ease of use, response to local variation, compatibility with existing classifications and compatibility with political jurisdictions. Of those methods meeting the above criteria the regional climatic classification chosen for this study considers the combination of incident solar radiation and heating/cooling degree days. This approach is intended to account for both solar energy input required by the passive and photovoltaic systems as well as the thermal loads to be met by the space conditioning system. Annual mean solar radiation (in kWh/M²-YR), and heating/cooling degree day regions are shown in Figures 3-1 and 3-2 respectively. General insolation and thermal characteristics of the Southwest, Northeast, and Southeast regions are summarized in the following discussion. Detailed descriptions of climate characteristics in each region are found in References 1,5,6.

FIGURE 3-1. ANNUAL MEAN DIRECT NORMAL SOLAR RADIATION (kWh/M²)
FIGURE 3-2. HEATING/CoolING DEGREE DAY REGIONS (base 18.3°C)

In the Southwest, annual average radiation ranges from 2230 to over 2635 kWh/M²-YR. The number of heating degree days may exceed 3889 (18.3°C), while the number of cooling degree days may exceed 1111.

In the Northeast, annual average radiation ranges from under 1015 to 1420 kWh/M²-YR. The number of heating degree days ranges from 2222 to more than 3889, while the number of cooling degree days is usually less than 1111.

In the Southeast, annual average radiation ranges from 1825 to 2230 kWh/M²-YR. The number of heating degree days may be as large as 3056, while the number of cooling degree days may exceed 1111.
3.3 Case Study Site Selection

Potential case study locations were limited to the approximately thirty cities that have been the subject of previous PV-feasibility studies in order to maximize the amount of available data and to facilitate future comparative research. Site locations in each region were then screened to select areas with population greater than 250,000. The next level of site selection considered the effect of insolation and temperature on PV and passive system performance.

An approach based on Bahm (7) to identify how available insolation and temperature in a region will affect PV and passive system performance concerns was developed correlating mean daily percent of extraterrestrial solar radiation ($K_T$) versus daily temperature ($^\circ$C). These correlations enable comparison of seasonal and location variations in thermal demands and available radiation to identify key passive and PV operating characteristics within each region.

Example plots within each region are shown in Figure 3-3. Warm days are represented on the right hand side of each plot, cold days on the left. Clear days are represented at the top of each plot, cloudy days at the bottom. These examples of regional patterns illustrate the abundance of clear days across a broad range of temperatures in the Southwest; the significance of cold, partly overcast days in the Northeast; and the extent of partly cloudy, mild weather in the Southeast. From these plots it was possible to identify representative site locations from a number of regional samples prior to detailed system simulation.

Typical Meteorological Year (TMY) weather data was chosen to document the climate characteristics of each site location. This weather data for 26 U.S. cities, available on magnetic tape from the National Climatic Center in Asheville, N.C., contains hourly insolation, temperature, relative humidity, and wind velocity. Those sites within the TMY data base that had received the highest ranking relative to prior use, population, and representative insolation and temperature correlation were selected for case study locations. The three locations ultimately chosen were Phoenix, AZ (Southwest); Boston, MA (Northeast); and Nashville, TN (Southeast).

3.4 Weather Data Comparison

Performance comparison of different solar systems and components has usually been made more difficult by the lack of universally accepted hourly meteorological data. Representative-year weather data used by GE and Westinghouse were compared with both TMY data and historical SOLMET averaged to identify differences in performance estimates resulting from their use.
FIGURE 3.2: REGIONAL PLOTS OF $r_1$ VS. TEMPERATURE (°C)

ALBUQUERQUE NM

PHOENIX AZ

FRESNO CA

BOSTON MA

CARIBOU ME

WASHINGTON DC

CHARLESTON SC

LAKE CHARLES LA

NASHVILLE TN
When the GE and Westinghouse studies began, the SOLMET data base represented the best source of real weather data. The SOLMET data base, produced by the National Oceanographic and Atmospheric Administration, contains 23 years of reformatted and rehabilitated records from 26 U.S. weather stations. Deficiencies corrected by the rehabilitation and reformatting procedures included machine-readable format and media inconsistencies and measurement gaps and inaccuracies (8,9). A reference year for each site was selected from the SOLMET data base by GE and Westinghouse using methods similar to the ASHRAE (10) technique.

As the GE and Westinghouse studies neared completion, development of TMY weather data was begun by Sandia National Laboratories. The objective was to establish commonly accepted hourly meteorological data for use in computer simulations of solar heating and cooling systems at each of the 26 cities included in the SOLMET data base. Unlike the SOLMET data base which consists of individual-year measurements, the TMY data base consists of a single "synthetic" year for each site. A typical month for each of the twelve calendar months was selected from the 23-year SOLMET data base for each site. Then the typical months were spliced together to form each TMY. Discontinuities in weather data at the beginning and end of each month were smoothed by interpolation (11). Table 3-1 lists the months used in the TMYs for Boston, Nashville and Phoenix.

<table>
<thead>
<tr>
<th>TABLE 3-1. MONTHS USED FOR TMYs FOR CASE STUDY LOCATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
</tr>
</tbody>
</table>

Subsequently, GE compared performance predictions based on its selected representative years with those using Westinghouse representative years and TMYs. Performance variation generally less than 10% was reported using the different weather data bases (3). Recently, a more extensive evaluation of the effect of different weather data on solar heating and cooling performance prediction was completed by Freeman (11). Although temperature and "persistance" biases in the TMY data base were noted, it was concluded that the TMYs best represent state-of-the-art weather data for solar system performance prediction.
The AIA/RC comparison of primary weather data of interest for Phoenix, Boston and Nashville indicated that the range of variation in insolation, heating degree day and cooling degree day data among the selected representative years, TMYs and SOLMET averages were generally less than 10%. Performance predictions using these different weather data sets showed similarly small differences in value. In general, agreement among solar irradiance values is closer than among values for heating or cooling degree days. Although heating degree days in the warm, arid Phoenix weather somewhat underestimate long-term conditions, the differences are negligible. Similarly, differences between cooling degree days and long-term averages in Phoenix and Boston are small. Differences between historical averages and selected data bases was more significant for Nashville cooling degree days. This location was the only one in which use of the TMY, GE or Westinghouse data yielded an average of less than 90% of the long term temperature conditions. These results agree with earlier comparisons of the synthetic and representative weather data sets. A comparative listing of weather data base differences is shown in Table 3-2 and illustrated in Figure 3-4.

### Table 3-2. Comparison of Data Bases for Case Study Locations

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>WEATHER DATA SOURCE</th>
<th>ANNUAL HEATING DEGREE DAYS (18.3°C base)</th>
<th>ANNUAL COOLING DEGREE DAYS (18.3°C base)</th>
<th>ANNUAL HORIZON SOLAR IRRAD. (kWh/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>% Dev.</td>
<td>Total</td>
</tr>
<tr>
<td>BOSTON</td>
<td>SOLMET Avg.</td>
<td>3123</td>
<td>----</td>
<td>367</td>
</tr>
<tr>
<td></td>
<td>TMY *</td>
<td>3190</td>
<td>2.1</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>1960 (GE)</td>
<td>3172</td>
<td>1.5</td>
<td>396</td>
</tr>
<tr>
<td></td>
<td>1965 (W)</td>
<td>3467</td>
<td>9.9</td>
<td>349</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>SOLMET Avg.</td>
<td>2053</td>
<td>----</td>
<td>841</td>
</tr>
<tr>
<td></td>
<td>TMY *</td>
<td>1980</td>
<td>3.7</td>
<td>869</td>
</tr>
<tr>
<td></td>
<td>1968 (GE)</td>
<td>2347</td>
<td>12.5</td>
<td>806</td>
</tr>
<tr>
<td></td>
<td>1966 (W)</td>
<td>2154</td>
<td>4.7</td>
<td>840</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>SOLMET Avg.</td>
<td>862</td>
<td>----</td>
<td>1949</td>
</tr>
<tr>
<td></td>
<td>TMY *</td>
<td>767</td>
<td>12.4</td>
<td>2026</td>
</tr>
<tr>
<td></td>
<td>1953 (GE)</td>
<td>832</td>
<td>3.6</td>
<td>1861</td>
</tr>
<tr>
<td></td>
<td>1967 (W)</td>
<td>795</td>
<td>8.4</td>
<td>1931</td>
</tr>
</tbody>
</table>
FIGURE 3-4. COMPARISON OF WEATHER DATA SETS
4.1 Summary

Loads considered in this study fall into three primary categories: base appliance loads for cooking, clothes drying, etc.; loads for domestic water heating; and loads for space conditioning. Estimating any of these loads in the mid-1980s presents uncertainties because of variations in equipment efficiency and use, seasonal and regional factors, residence construction characteristics, and the effect of energy conserving behavior patterns. This section describes the assumptions, methods, and data used to generate these estimates.

Since the focus of this report was passive heating, all components contributing to heating loads were reviewed, evaluated and combined into final estimates for variable analyses. As DHW and base appliance loads had already been sufficiently detailed in previous (3,4) studies, they were assumed directly from these works and used without modification. These are reviewed in the following pages.

The residential loads defined in the previous studies, were based on the living patterns for an average size family of 4-5 members in single family detached housing expected for the middle-income mass market. Loads for base appliances, domestic water heating and space conditioning were projected for 1986 using estimates of energy conservation applied to 1978 levels. In the 1978 and 1986 mean annual loads listed in Table 4-1 for an all-electric non-solar residence, heating and cooling loads are shown for a 139.4 m² (1500 ft²) floor area.

### TABLE 4-1. ANNUAL 1978 AND 1986 ALL-ELECTRIC RESIDENCE LOADS (kWh)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>APPLIANCES</th>
<th>DHW</th>
<th>HEATING</th>
<th>COOLING</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASHVILLE</td>
<td>7520 6844</td>
<td>5348 4813</td>
<td>8066 4033</td>
<td>1010 505</td>
<td>21944 16195</td>
</tr>
<tr>
<td></td>
<td>7520 6844</td>
<td>5348 4813</td>
<td>8066 4033</td>
<td>1010 505</td>
<td>21944 16195</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>7520 6844</td>
<td>4457 4011</td>
<td>4537 2269</td>
<td>4867 2434</td>
<td>21381 15558</td>
</tr>
<tr>
<td></td>
<td>7520 6844</td>
<td>4457 4011</td>
<td>4537 2269</td>
<td>4867 2434</td>
<td>21381 15558</td>
</tr>
<tr>
<td></td>
<td>4099 3689</td>
<td>1712 556</td>
<td>5409 2705</td>
<td>18740 14094</td>
<td></td>
</tr>
</tbody>
</table>
Mean annual loads for non-solar residences in the mid-1980s were estimated to be an average of 33% less than 1978 loads for the case study cities. These levels of energy conservation include a 9% reduction in base appliance loads and a 10% reduction in domestic water heating loads. However, the largest reductions are expected in space conditioning loads. Heating and cooling loads are expected to be 50% of those in 1978.

Space conditioning demand in 1978 and 1986 Boston, Nashville and Phoenix residences were scaled from a normal distribution of heating and cooling performance developed from survey data. Heating and cooling performance of the GE and Westinghouse prototypes are shown with mean, 20th and 80th percentiles of this distribution in Table 4-2. These values were normalized for differences in residence size and weather data to facilitate comparison.

TABLE 4-2. COMPARISON OF HEATING AND COOLING DEMANDS (kWh/DDc-M²)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEMAND</th>
<th>1978 RESIDENCES</th>
<th>1986 RESIDENCES</th>
<th>PROTOTYPES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>20th Mean 80th</td>
<td>20th Mean 80th</td>
<td>GE WEST.</td>
</tr>
<tr>
<td>BOSTON</td>
<td>HEATING</td>
<td>.045 .058 .069</td>
<td>.023 .029 .035</td>
<td>.018 .019</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.043 .052 .060</td>
<td>.022 .026 .030</td>
<td>.044 .049</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>HEATING</td>
<td>.040 .051 .060</td>
<td>.020 .026 .030</td>
<td>.016 .021</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.030 .037 .057</td>
<td>.015 .019 .029</td>
<td>.036 .052</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>HEATING</td>
<td>.029 .048 .066</td>
<td>.015 .024 .033</td>
<td>.006 .018</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.031 .036 .039</td>
<td>.016 .018 .020</td>
<td>.045 .049</td>
</tr>
</tbody>
</table>

In all cases, the prototypes show lower heating demand than expected for the average 1986 residence. In most cases, the prototypes show lower heating demand than expected for more than 80% of the residences. The prototype heating demands reflect their use of more insulation, and infiltration reductions. The prototypes show higher cooling demands than expected for the average 1986 residence. The cooling demands reflect their use of more south-facing glazing than generally employed. Despite these differences, the seasonally weighted annual values for the prototypes adequately exhibit demands expected for 1986 residences.
4.2 Base Appliance and Domestic Hot Water Loads

The base appliance system used in this study consists of lights and appliances, clothes dryer, cooking range and other cooking appliances as well as ancillary HVAC equipment such as blowers, pumps, fans and controls. The system is supplied with 120 Vac, 10, 60 Hz and 240 Vac, 10, Hz residential power service.

The load may be estimated from the duty cycle of all base load appliances, or from comparative data for similar residences using utility bills or correlated relationships. A duty cycle estimate of the average daily load can be prepared using the following formula:

\[
L_B = \sum_{i=1}^{N} (P \times T \times C)_i
\]

where 
- \( L_B \) = average daily base appliance load in kWh
- \( N \) = number of base load appliances
- \( P \) = average operating power in kW
- \( T \) = elapsed time of use in hrs.
- \( C \) = "on" - cycle fraction for thermostatically controlled devices

This formula was applied to data from similar residences modified by occupancy and equipment usage factors in order to provide the estimates of demand used in this study. A number of references (1,3,4,12) were compared both for estimates of current demand as well as projections of demand in the mid 1980s.

It was found from these references that several factors significantly influence base load level. These factors include: family age and income; number of residents; weather conditions; floor area; and energy conservation practices.

Comparison of current estimates show negligible differences on an annual basis. No regional adjustment factors were found to significantly reflect the impact of weather conditions on base load beyond the seasonal factors. Factors of 1.18 for winter, 0.94 for spring, 0.86 for summer and 1.03 for fall were found to characterize the modification of average daily base load for seasonal use. Use of adjustments for weekend and vacation occupancy were not found to significantly affect estimates of base load.
Mean annual base loads were estimated to be 7520 kWh in 1978 for Boston, Nashville and Phoenix. General Electric estimated that reductions in appliance use and equipment efficiency losses would result in a 9% reduction in this load in 1986. This reduction yielded a projected annual load of 6844 kWh.

An average of 53% of the daily base appliance load was estimated to occur during the daytime, between sunrise and sunset. Since expected base load reductions found in the literature were given for annual energy use, no assumptions were made concerning the shift of nighttime loads into the day as a load management action for the PV system. It was assumed that the magnitude of the 1978 daily base electrical load profile was diminished uniformly over a 24-hour period for the 1986 projections.

A summary of base appliance energy consumption is shown in Table 4-3.

### TABLE 4-3. REFERENCE BASE APPLIANCE LOADS (in kWh)
FOR BOSTON, NASHVILLE AND PHOENIX

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>397</td>
<td>361</td>
<td>754</td>
<td>686</td>
</tr>
<tr>
<td>FEB</td>
<td>358</td>
<td>326</td>
<td>681</td>
<td>620</td>
</tr>
<tr>
<td>MAR</td>
<td>315</td>
<td>287</td>
<td>600</td>
<td>546</td>
</tr>
<tr>
<td>APR</td>
<td>305</td>
<td>278</td>
<td>582</td>
<td>530</td>
</tr>
<tr>
<td>MAY</td>
<td>315</td>
<td>287</td>
<td>600</td>
<td>546</td>
</tr>
<tr>
<td>JUN</td>
<td>279</td>
<td>254</td>
<td>532</td>
<td>484</td>
</tr>
<tr>
<td>JUL</td>
<td>289</td>
<td>263</td>
<td>549</td>
<td>500</td>
</tr>
<tr>
<td>AUG</td>
<td>289</td>
<td>263</td>
<td>549</td>
<td>500</td>
</tr>
<tr>
<td>SEP</td>
<td>335</td>
<td>305</td>
<td>637</td>
<td>580</td>
</tr>
<tr>
<td>OCT</td>
<td>346</td>
<td>315</td>
<td>659</td>
<td>600</td>
</tr>
<tr>
<td>NOV</td>
<td>335</td>
<td>305</td>
<td>637</td>
<td>580</td>
</tr>
<tr>
<td>DEC</td>
<td>397</td>
<td>361</td>
<td>754</td>
<td>686</td>
</tr>
<tr>
<td>ANN</td>
<td>3961</td>
<td>3605</td>
<td>7520</td>
<td>6844</td>
</tr>
</tbody>
</table>
The domestic hot water DHW system used in this study consisted of an electric resistance water heater supplied with 240 Vac, 10, 60 Hz power. The load may be estimated from water temperature, water consumption, and equipment efficiency or from comparative data for similar residences using utility bills or correlated relationships. An estimate of the average daily load based upon water temperature, volume and equipment characteristics can be prepared using the following formula:

\[ L_D = 1.16 \times (T_o - T_i) \times R \times S / \text{COP} / (1 + W) \]

where \( L_D \) = average daily hot water load in kWh
\( T_o \) = outlet water temperature in °C
\( T_i \) = inlet water temperature in °C
\( R \) = number of residents
\( S \) = daily water consumption in M³ per resident
\( \text{COP} \) = heater coefficient of performance
\( W \) = fraction of stored heat lost through tank walls

The value 1.16 is the energy in kWh required to raise 1 M³ of water 1 °C. A typical value of \( T_o \) is 60°C (140°F). A typical value of \( S \) is 0.08 M³ (20 gallons) per person. The average COP for an electric resistance water heater is usually estimated as unity. For a 40 gallon (0.150 M³) tank, the fraction of energy lost is estimated as .20 (3). Estimates of demand used in this study were based upon data from similar residences as well as occupancy and equipment factors. A number of references (3,4,13) were compared both for estimates of current demand as well as projections of demand in the mid 1980s. It was found from these references that several factors significantly influence the DHW load level. The factors include: family age and income; number of residents; weather conditions; equipment characteristics; and energy conservation practices.

Comparison of current estimates show negligible differences on an annual basis. No seasonal adjustment factors were found to significantly reflect the impact of weather conditions on DHW load beyond the regional factors. Typically groundwater temperatures are assumed to occur within a 5.5°C (10°F) range about the average daily ambient temperature. Daily ambient air temperature assumed for the case study locations were 10.7°C (51.3°F) for Boston, 15.2°C (59.4°F) for Nashville and 21.3°C (70.3°F) for Phoenix. Use of adjustment factors for weekend and vacation use were not found to significantly affect estimates of the DHW load.
Mean annual DHW loads in 1978 were estimated to be 5348 kWh for Boston, 4457 kWh for Nashville and 4099 kWh for Phoenix. It was estimated that reductions in outlet water temperature and usage would result in a 10% reduction of this load in 1986 (3). This reduction yielded a projected annual load of 4813 kWh in Boston, 4011 kWh in Nashville and 3689 kWh in Phoenix.

An average of 73% of the daily DHW load was estimated to occur during the daytime, between sunrise and sunset. Since expected DHW load reductions found in the literature were given for annual energy use, no assumptions were made concerning the shift of nighttime loads into the day as a load management action for the PV system. It was assumed that the magnitude of the 1978 daily DHW load profile was diminished uniformly over a 24-hour period for the 1986 projections.

A summary of DHW energy consumption is shown in Tables 4-4 and 4-5.

4.3 Heating, Ventilation and Air Conditioning Loads

The heating, ventilating and air conditioning (HVAC) plant used in this study consists of an air-to-air heat pump and an electric resistance backup supplied with 240 Vac, 1o, 60 Hz power. The HVAC load depends on resident comfort, residence characteristics and equipment efficiency.

The load may be calculated from weather, occupancy and equipment performance data or estimated from comparative data for similar residences using utility bills or correlated relationships. Using weather occupancy and equipment data the load can be calculated according to the following formula:

\[
L_{HC} = \left(\frac{1}{\text{COP}}\right) \sum_{i=1}^{24} \left\{ \left(\text{UA} \times (T_{\text{amb}} + T_{\text{set}})\right) + Q_{\text{int}} \right\}
\]

where
- \(L_{HC}\) = average daily heating or cooling demand (kWh)
- \(T_{\text{amb}}\) = ambient hourly temperature
- \(T_{\text{set}}\) = thermostat set temperature (C)
- \(Q_{\text{int}}\) = average internal heat generation (kW)
- \(\text{UA}\) = adjusted heat conductance-area product (kW)
- \(\text{COP}\) = average coefficient of performance (including resistance backup for heat pumps).
### TABLE 4-4. REFERENCE 1978 DOMESTIC HOT WATER LOADS (in kWh)

<table>
<thead>
<tr>
<th>MONTH</th>
<th>BOSTON MONTHLY</th>
<th>BOSTON DAYTIME</th>
<th>NASHVILLE MONTHLY</th>
<th>NASHVILLE DAYTIME</th>
<th>PHOENIX MONTHLY</th>
<th>PHOENIX DAYTIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>JAN</td>
<td>454</td>
<td>10.59</td>
<td>379</td>
<td>8.82</td>
<td>348</td>
<td>8.10</td>
</tr>
<tr>
<td>FEB</td>
<td>410</td>
<td>10.59</td>
<td>342</td>
<td>8.82</td>
<td>314</td>
<td>8.10</td>
</tr>
<tr>
<td>MAR</td>
<td>454</td>
<td>10.59</td>
<td>379</td>
<td>8.82</td>
<td>348</td>
<td>8.10</td>
</tr>
<tr>
<td>APR</td>
<td>440</td>
<td>10.59</td>
<td>366</td>
<td>8.82</td>
<td>337</td>
<td>8.10</td>
</tr>
<tr>
<td>MAY</td>
<td>454</td>
<td>10.59</td>
<td>379</td>
<td>8.82</td>
<td>348</td>
<td>8.10</td>
</tr>
<tr>
<td>JUN</td>
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<td>366</td>
<td>8.82</td>
<td>337</td>
<td>8.10</td>
</tr>
<tr>
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<td>454</td>
<td>10.59</td>
<td>379</td>
<td>8.82</td>
<td>348</td>
<td>8.10</td>
</tr>
<tr>
<td>AUG</td>
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<td>8.10</td>
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<tr>
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<td>10.59</td>
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<td>8.82</td>
<td>337</td>
<td>8.10</td>
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<tr>
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<td>8.82</td>
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<td>8.10</td>
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<td>4457</td>
<td>3220</td>
<td>4099</td>
<td>2957</td>
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</table>

*Figures may not total due to round-off errors.

### TABLE 4-5. REFERENCE 1986 DOMESTIC HOT WATER (DHW) LOADS (in kWh)

<table>
<thead>
<tr>
<th>MONTH</th>
<th>BOSTON MONTHLY</th>
<th>BOSTON DAYTIME</th>
<th>NASHVILLE MONTHLY</th>
<th>NASHVILLE DAYTIME</th>
<th>PHOENIX MONTHLY</th>
<th>PHOENIX DAYTIME</th>
</tr>
</thead>
<tbody>
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<td>JAN</td>
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<td>9.53</td>
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<td>7.94</td>
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<td>7.29</td>
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<tr>
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<td>330</td>
<td>7.94</td>
<td>303</td>
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<td>3478</td>
<td>4011</td>
<td>2898</td>
<td>3689</td>
<td>2661</td>
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</table>

*Figures may not total due to round-off errors.
Several steps were followed to estimate the HVAC load in the mid 1980s. First, space conditioning demand estimates for typical residences in 1978 were obtained (1). Energy conservation strategies from similar residences, as well as occupancy factors were then used to project typical space conditioning demand in 1986 (5,14,15,16). Typical 1986 demands were compared with demands from the residential prototype designs developed by Burt Hill Kosar Rittelmann Associates for Westinghouse (4), and Massdesign for General Electric (3). Finally, performance characteristics of a heat pump/resistance-backup plant under development for the mid-1980s were used to convert the typical 1986 space conditioning demands to an HVAC load.

Estimates of the designed energy performance of 1978 residential buildings were based on actual buildings throughout the continental United States. Estimates of energy used for heating and cooling single family detached residences were taken from a sample of 128,000 homes. Energy consumption variables reported in this study (1) included heat transfer rates for building component sections, seasonal efficiencies for heating and cooling equipment as well as adjustment factors for house type (e.g., one-story, two-story, bi-level and split-level).

Space conditioning demand for 1978 residences in Boston, Nashville and Phoenix were scaled from a normal distribution of energy performance. Mean, 20th and 80th percentiles of space conditioning demand are shown in Table 4-6.

### TABLE 4-6. COMPARISON OF HEATING AND COOLING DEMANDS (kWh/DDC-M²)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DEMAND</th>
<th>1978 RESIDENCES</th>
<th>1986 RESIDENCES</th>
<th>PROTOTYPES</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>20th</td>
<td>Mean</td>
<td>80th</td>
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<tr>
<td>BOSTON</td>
<td>HEATING</td>
<td>.045</td>
<td>.058</td>
<td>.069</td>
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<tr>
<td></td>
<td>COOLING</td>
<td>.043</td>
<td>.052</td>
<td>.060</td>
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<tr>
<td>NASHVILLE</td>
<td>HEATING</td>
<td>.040</td>
<td>.051</td>
<td>.060</td>
</tr>
<tr>
<td></td>
<td>COOLING</td>
<td>.030</td>
<td>.037</td>
<td>.057</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>HEATING</td>
<td>.029</td>
<td>.048</td>
<td>.066</td>
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<tr>
<td></td>
<td>COOLING</td>
<td>.031</td>
<td>.036</td>
<td>.039</td>
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</table>
Reasonable expectations of long-term levels of space conditioning demand were based upon surveys of energy conscious design practices (5,16,16) and performance data of energy conserving residences (5,12,14). These expectations reflect marketability in housing rather than maximum technical feasible performance. Energy conscious design practices are expected to include proper design of the building envelope, recovery of heat generated by normal indoor activities, and distribution of solar heat gain.

Proper design of the building envelope to control interior temperature can be achieved by insulation, thermal-lag and ventilation through the structure. Use of thermal-lag effect is more applicable in climates with appreciable ambient temperature swings, where nighttime temperatures are significantly lower than those in the day.

In well-insulated dwellings, normal indoor activities such as cooking, bathing, breathing, and perspiration provide an ample source of heat and moisture when ambient temperatures are moderate. Recovery of this heat together with the use of ventilation, or interior air movement, can provide adequate temperature and not exceed humidity limits. Distribution of solar heat gain or suntempering is expected to supply comfortable daytime temperatures, depending on the structural properties of the building and the availability of sunshine during the heating season. At lower ambient temperatures, a mechanically assisted means of heating is required (16, 17).

On the basis of field experience already achieved, AIA/RC expects space conditioning demands in 1986 projected from the use of these practices to reduce 1978 levels by 50% in the absence of any suntempering contribution. When credit is taken for solar heat gain, 1986 demands are expected to be 34% of 1978 levels. Demands for Boston, Nashville and Phoenix are shown in Table 4-6.

Primary issues considered in the comparison and review of the prototypes were representation of comfort conditions, heat loss/gain, equipment loads, and energy consumption. Although the degree of detail in reporting space conditioning demands varied between the thermal models used, the prototypes were found to be quite similar when normalized for different assumptions in weather conditions (i.e., heating degree days) and floor area.

A simplification of the thermal model used in the GE study is illustrated in Figure 4-1. As shown, nodes within walls are replaced by conductances between global zone nodes.

A simplification of the steady-state thermal model used by Westinghouse is shown in Figure 4-2.
**FIGURE 4-1. GE THERMAL NETWORK MODEL**

BOSTON SINGLE-FAMILY DETACHED RESIDENCE

- \( T_a \) = OUTSIDE AIR TEMPERATURE
- \( T_e \) = UNHEATED ATTIC OVER GARAGE
- \( T_r \) = UNHEATED ATTIC OVER ZONE 2
- \( T_u \) = UNHEATED GARAGE, EQUIPMENT ROOM
- \( Z_1 \) = ZONE ONE: LIVING, DINING, KITCHEN, CLERESTORY
- \( Z_2 \) = ZONE TWO: BEDROOMS, BATH AREAS

NASHVILLE AND PHOENIX SINGLE-FAMILY DETACHED RESIDENCE

**FIGURE 4-2. WESTINGHOUSE THERMAL MODEL**

- Graphs showing the variation of condition load with outdoor temperature for Boston, Nashville, and Phoenix.
Monthly heating and cooling demands were tabulated for the GE and Westinghouse prototypes in Boston, Nashville and Phoenix using their respective thermal models. These demands are shown in Table 4-7. Next, these demands were converted into values expressed as kWh/DD - M² floor area. Converted values are shown in Table 4-7. These values were then ranked within the normal distribution of typical 1986 demands.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>FLOOR AREA (M²)</th>
<th>DEGREE DAYS (18.3°C)</th>
<th>LOAD (kWh)</th>
<th>OTTV (kWh/DD/M²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEATING</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>GE</td>
<td>145</td>
<td>3172</td>
<td>8419</td>
<td>0.018</td>
</tr>
<tr>
<td>W</td>
<td>167</td>
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<td></td>
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<tr>
<td>GE</td>
<td>145</td>
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<tr>
<td>GE</td>
<td>141</td>
<td>2347</td>
<td>5214</td>
<td>0.016</td>
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<td>162</td>
<td>2154</td>
<td>7421</td>
<td>0.021</td>
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<tr>
<td>COOLING</td>
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<tr>
<td>GE</td>
<td>141</td>
<td>806</td>
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<tr>
<td>W</td>
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<tr>
<td>COOLING</td>
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<tr>
<td>GE</td>
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<td>11871</td>
<td>0.045</td>
</tr>
<tr>
<td>W</td>
<td>155</td>
<td>1931</td>
<td>14656</td>
<td>0.049</td>
</tr>
</tbody>
</table>
In all cases, the prototypes show lower heating demand than expected for the average 1986 residence. In most cases, the prototypes show lower heating demand than expected for more than 80% of the residences. The prototype heating demands reflect their use of more insulation, and infiltration reductions. The prototypes show higher cooling demands than expected for the average 1986 residence. The cooling demands reflect their use of more south-facing glazing than generally employed. Despite these differences, the seasonally weighted annual values for the prototypes adequately exhibit demands expected for 1986 residences.

The performance characteristics of an advanced heat pump system previously reported under development by GE (3) were represented by both heating/cooling capacities and COP as a function of the ambient dry-bulb temperature. A nomograph of these relationships is shown in Figure 4-3. The heat pump outdoor coils will accumulate frost at approximately 4.4°C (40°F). It was assumed that defrosting was required at the following temperature and humidity conditions:

\[-2.2°C \leq T_{OD} \leq 3.9°C; \text{ and } \frac{(1.8T_{OD} + 72)}{100} \leq RH \leq 1.00\]

where

\[RH = \text{relative humidity}\]
\[T_{OD} = \text{outside dry bulb temperature °C}\]

During defrost conditions, the total input power that the heat pump and electric resistance heater will need is 1.1 \(P_{HP}\), where \(P_{HP}\) is the heat pump power without defrosting. Power input for the electric resistance heater (\(P_{RH}\), with heat pump defrosting is:

\[P'_{RH} = P_{RH} + \frac{0.1C_{HP}}{\text{COP}_{RH}}\]

where

\[P_{RH} = \text{resistance heater power without heat pump}\]
\[C_{HP} = \text{heat load without heat pump defrosting}\]
\[\text{COP}_{RH} = \text{resistance heat COP}\]
FIGURE 4-3. ADVANCED HEAT PUMP CHARACTERISTICS
4.4 Summary of Loads

Residential loads were based on the 1978 and 1986 mean annual loads listed in Table 4-8 for an all-electric non-solar residence; heating and cooling loads are shown for a 139.4 m² (1500 ft²) floor area.

<table>
<thead>
<tr>
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<td>18740</td>
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SECTION 5.0

SOLAR ENERGY SYSTEMS DEFINITION

5.1 Summary

The residential PV and passive systems considered in this study are generic in that each utilizes a roof-mounted PV array, has no on-site storage, provides a utility connection which allows two-way flow, and relies upon a combination of direct and non-direct passive heating savings. Figure 5-1 shows a block diagram for a generic utility-interactive PV and passive heating system.

FIGURE 5-1
RESIDENCE BLOCK DIAGRAM

The photovoltaic system consists of the following elements: a flat-plate, roof-mounted, passively-cooled array; balance of system wiring; and a power conditioner. The passive system consists of the following elements: a collector; absorber; thermal storage; thermal distribution; and heat regulation devices or controls.
Operation of the PV and passive systems for the all-electric residence is assumed to occur according to the following logic:

- The passive collector admits solar radiation onto the absorber that "converts" radiation to heat. Heat not used for space conditioning is delivered to storage for later distribution to the living spaces.

- The PV array converts solar radiation to DC electricity for input to the power conditioner. That DC input is converted to AC power to meet the residence's space conditioning, base appliance, and domestic water heating loads.

- When thermal loads are not fully met by the passive system, the balance of the space conditioning load is supplied by the auxiliary air-to-air heat pump. Under those ambient temperature and humidity conditions that preclude heat pump operation, back-up heating is supplied by electric resistance units.

- When electrical loads are not satisfied by the PV system, auxiliary power is drawn from the utility grid. When PV system output exceeds electrical loads, that excess power is fed back to the utility.

An illustration of the generic PV system considered in this study is shown in Figure 5-2. The elements depicted are specified in more detail in Section 5-2.
Schematic illustrations of the types of passive systems considered in this study are shown in Figure 5-3. The elements depicted are specified in more detail in Section 5-3.

**FIGURE 5-3. SCHEMATIC ILLUSTRATIONS OF PASSIVE SYSTEMS**
5.2 Photovoltaic System Definition

Photovoltaic systems that were the focus of this study were utility-interactive installations without storage, having system output between 4 kW and 8 kW. Utility interactive systems were studied because energy feedback from the PV system is generally valued by the utility (18). Dedicated on-site storage appears viable only when low cost is coupled with a low (0.35) sellback/purchase ratio (4). Previous studies have indicated interactive systems are viable without storage in the Southwest, Northeast and Southeast at sellback/purchase ratios not less than 0.5 (3,18). The system output range was selected to satisfy constraints on array sizing. The two constraints considered are: 1) non area-dependent system energy costs rise rapidly below 4 kWp for systems in the $2 - $3/Wp range and 2) the array should not exceed the available roof area (19). If the systems are sized on a “zero net annual energy use” basis, the 4 kWp size appears capable of satisfying diversified-load-only applications, and avoid most fixed cost penalties, while the 8 kWp size appears capable of satisfying all-electric load applications, yet small enough to fit most roofs (20).

The photovoltaic array consists of a set of modules that convert sunlight into DC power. In the array subsystem, modules are connected in series to form branch circuits that input voltage to the power conditioner. Branch circuits are connected in parallel to develop current input to the power conditioner. A representative Nominal Operating Cell Temperature (NOCT) was chosen to allow module mounting by any of the following methods: integral, direct, standoff, or rack.

Each module contains parallel strings of cells to develop current and series cell blocks to develop voltage potential. Roof mounted modules were specified as flat-plate, fixed-tilt and passively cooled with a 20 year service life. Square, 10 cm x 10 cm, single or semicrystalline silicon cells were assumed to reflect a trend in module design toward high density cell packing. Modules were configured with 36 series cells, 2 parallel strings and 3 bypass diodes. Module area equalled .722 m² (2' x 4' nom). Peak module power (Pp) was established at 97.2 W per module, with nominal operating voltage (V_{NO})* of 16.6 volts at 1 kW/m², AM 1.5 and 25°C cell temperature. Operating Cell Temperature (NOCT) of 60°C, module output power (P_{avg}) was established at 74.3 W, 15.8V at 800 W/m² and AM 1.5. This yielded an annual average module efficiency of 9.3%. Temperature-power, -current, and -voltage coefficients used were respectively -0.0004W/(°C, 0.005 amperes/°C, and -0.086 volts/°C.

* V_{NO} is the peak voltage occurring at maximum module power under nominal operating conditions (NOC), see reference (21).
The array wiring configuration was assumed to consist of five branch circuits of thirteen modules for a four kWp system and ten branch circuits of thirteen modules for an 8 kWp system. Array wiring includes branch circuit wiring harnesses between modules, busbars for branch circuit connection, outdoor and indoor electrical disconnects, ground straps, high voltage protection, and over-current protection. Array wiring was assumed to consist of 14 AWG harnesses, each less than 2 FT in length, with 10 AWG bus cables. An earth ground wire was specified from any metallic array frame to eliminate shock hazard due to static charge buildup or cell-to-frame fault. Varistors were considered adequate high voltage surge protection for the low isokeraunic levels assumed. Array isolation from the power conditioner during inverter maintenance was assumed accomplished by an indoor manual disconnect. Power losses through this wiring system were estimated as 2% of the total array output.

The power conditioner converts DC power from the array to AC power for the residence and contains system controls. In normal operation, automatic start-up in the morning, shut-down in the evening, and array voltage control is accomplished. In addition, system control in the power conditioner automatically disconnects the photovoltaic system from the utility in the event of utility power loss.

Advanced design 4 kVA, 6 kVA, and 10 kVA power conditioning units were selected from a breadboard design (22) to provide 240 Vac, 60 Hz, single phase output voltage from an array input voltage range of 160-240 Vdc. Each unit contained a maximum power tracking system controller, a transistorized power bridge and a digital output controller. Efficiency used over the power range was 90% from 25% of the load to full load. No-load losses were limited to 2.5% of rated power. Other specifications included 5% THD injected current harmonic distortions and unity power factor. A nominal input voltage of 200 Vdc was accompanied by automatic startup at 180 Vdc and automatic turn-off at 160 Vdc and 260 Vdc. Automatic disconnects were assumed to occur at a utility voltage above 264 Vac, below 216 Vac, beyond rated current, output frequency out of phase, or loss of utility power. Automatic turn-off was also assumed for power transistor temperature protection.

Reference values of PV systems defined are shown in Figure 5-4.

5.3 Passive System Definition

In a passive heating or cooling system, heat is distributed through a building by natural means. Many of the components of a passive solar system serve dual functions. For example,
FIGURE 5-4
STANDARDIZED VALUES OF UTILITY INTERACTIVE SYSTEMS CONSIDERED

Array Specs
Output: 4 KW, 6 KW, 8 KW
Cooling: Passive
Service Life: 20 years
Type: Roof mount, flat plate, fixed tilt at lat. - 10°

Module Specs
Pp: 134 W
V_{no}: 23.5 V at 1000 W/m² and AM 1.5 with cell temp. 25°C.
Output Power: 74.3 W, 15.8 V at 800 W/m² and AM 1.5 with NOCT of 60°C.
Average Annual Efficiency: 9.3%
Temp. Coefficients: -0.0004 W/°C, 0.005 Amperes/°C, -0.086 Volts/°C

Wiring Specs
Harnesses: 14 AWG, less than 2' length w/10 AWG bus cables
Wiring Power Losses: 2% of total array output

Power Conditioner Specs
Capacity: 4 KVA, 6 KVA, 8 KVA
Output: 240 Vac/60 HZ/1Ø
Input: 160-240 Vdc
Characteristics: Maximum power tracking system controller
Transistorized power bridge
Digital output controller
Efficiency Over Power Range: 90% from 25%-100% of load
No-Load Losses: 2.5% rated power
one component may provide enclosure and structural stability as well as collecting, storing, and distributing solar energy. The system is intrinsic to the building, affected by its site, orientation, floor plan, circulation patterns, window placement, and building materials. A well-designed passive heating system integrates five interacting elements: collector, absorber, storage, distribution, and heat regulation (5,4).

- The solar collector is an area of transparent or translucent glazing located on the south-facing side of the home. The collector surface can be positioned vertically, as in windows, or sloped, as in a skylight on the roof, and should be oriented to the south, plus or minus 30 degrees.

- The absorber is a solid surface, usually dark colored, that is exposed to winter sunlight entering through the collector. The absorber "converts" the solar radiation into heat which is then available for transfer to a storage medium.

- The storage medium is a dense material that holds heat transferred to it from the absorber. The storage medium should be of an appropriate volume and depth to hold the amount of solar heat collected, and is usually located in or adjacent to the rooms it is intended to heat. The absorber surface and storage medium may be one and the same, as in a brick floor or masonry wall.

- The distribution element of a passive system is the method by which heat is delivered to the living areas. Distribution can occur totally by natural means, such as radiation and natural convection, or can be assisted by small fans or pumps to direct heat to rooms away from the collector area or into remote storage.

- The heat regulation device, often termed the "control," can be an insulating medium to reduce heat loss through the collector during winter nights or cloudy periods, or a shading or a venting device to reduce heat gain during the summer.

The size and placement of the passive collector and storage are responsible for overall thermal performance since the system is driven by sunlight through the collector, and kept working during the night and cloudy periods by storage. The relationship of collection, storage and other elements to the living areas defines one of three generic system types used to heat a home: direct gain, indirect gain, or isolated gain. Examples of each system type were selected for study as marketable systems in the mid-1980s.
The direct gain system is the most widely used passive solar building solution. With direct gain, the occupants are in direct contact with all elements of the solar system—collector, absorber, storage, distribution, and controls. The basic characteristics of the direct gain building are: a large south-facing collector area, with the living areas exposed directly behind; absorber/storage floors and walls uniformly exposed to sunlight; and movable insulation for heat retention, which is distributed by radiation and natural convection. Variations in the direct gain system occur with storage and control options. Mechanical redistribution systems are sometimes used to control overheating by ducting excess heat to other rooms or to a secondary storage area that can be drawn on when heat is needed. Reference system parameters used in the analysis are listed in Figure 5-5 (16,23,24,25).

Indirect gain system designs range from a collector placed in front of a solid, unvented masonry wall that supplies only radiant heat to the house, to a collector in front of a masonry wall with a number of openings to allow light into the living spaces and facilitate the distribution of heat to the house by convection from the cavity between the wall and the glazing. The selection of a material and its thickness determines the wall's ability to store and distribute heat to the living spaces during the desired time period. Radiant distribution from the wall can be delayed up to 12 hours, depending on the depth of the wall and the heat-storing properties of the wall's construction, while convective distribution can begin almost immediately.

A Trombe wall combines radiant distribution with a convection "loop" that draws cool air from inside the house through low wall vents and delivers warmed air back to the house through upper wall vents. Any openings in the Trombe wall for daylighting are glazed to prevent a breakdown of the convective loop. During winter nights, an insulating curtain between the wall and the collector prevents reradiation of heat from the wall to the outside. The wall is shaded in the summer by closing the upper wall vent and opening an outside port at the top of the collector. Hot air exhausted to the outside by natural convection is replaced by cooler air drawn through opened windows on the north and across the house. Reference system parameters used to initiate the analysis are listed in Figure 5-6 (16,23,24,25).

In the isolated gain system, the passive collection and storage elements are in a secondary space that is separate from the main living space while distributing heat to the living areas. Solariums, greenhouses, sunspaces, and atriums are common examples of the secondary space in an isolated gain system.
FIGURE 5-5
STANDARDIZED VALUES OF DIRECT GAIN SYSTEMS CONSIDERED

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<thead>
<tr>
<th>Solar Aperture</th>
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</thead>
<tbody>
<tr>
<td>Number of glazings</td>
</tr>
</tbody>
</table>
| Glass transmissivity  
(at normal incidence) | 0.747               |
| Orientation                       | Vertical and south facing |
| Load per aperture area            | 1.0 BTU/hr.-°F-ft² |

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<tr>
<td>Thermal Conductivity</td>
</tr>
<tr>
<td>Heat Capacity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Surface Solar Absorptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Air Temperature Range in Building</th>
</tr>
</thead>
<tbody>
<tr>
<td>65°F to 75°F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Night Insulation (if used)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation in place from 5 p.m. to 7 a.m.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mass Surface to Room Air Conductance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 BTU/hr-ft²-°F</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ground Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overhand</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
</tr>
</tbody>
</table>

*Note: In order to account for the presence of furnishings and other low thermal capacity objects in the direct gain enclosure, it is assumed that 20% of the transmitted solar energy is absorbed and reradiated into the room air.*
### FIGURE 5-6

**STANDARDIZED VALUES OF GLAZED MASONRY WALL SYSTEMS CONSIDERED**

<table>
<thead>
<tr>
<th>Solar Aperture</th>
<th>Number of glazings</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass transmissivity (at normal incidence)</td>
<td>0.747</td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>Vertical and south facing</td>
<td></td>
</tr>
<tr>
<td>Thermal Storage</td>
<td>Thermal Storage</td>
<td>45 BTU/°F-ft(^2)</td>
</tr>
<tr>
<td>Building Mass</td>
<td>Negligible</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.0 BTU/ft·hr·°F</td>
<td></td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>30 BTU/ft(^3)·°F</td>
<td></td>
</tr>
<tr>
<td>Wall Absorptance</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>Air Temperature Range in Building</td>
<td>65°F to 75°F</td>
<td></td>
</tr>
<tr>
<td>Night Insulation (if used)</td>
<td>R9 Insulation in place from 5 p.m. to 7 a.m.</td>
<td></td>
</tr>
<tr>
<td>Wall to Room Air Conductance</td>
<td>1.0 BTU/hr·°F·ft(^2)</td>
<td></td>
</tr>
<tr>
<td>Ground Reflectance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No shadings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trombe Wall has vents with backdraft dampers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In these variations, sunlight enters the secondary space and strikes an absorber surface that transfers heat to storage. Because these secondary spaces can reach high daytime temperatures, provision is often made for ducting heat to a remote storage area. The sizing and location of storage within the secondary space depends on whether the space is to be used during the evening hours and whether the storage in the space continues.

Three distribution schemes are common for this system type. Vents, windows, and doors can be opened during the day to allow a convective flow of heat from the secondary space/storage into the main living spaces. Radiant distribution of heat stored in the common walls between the secondary and living spaces is also common. Fans are often used to charge or distribute heat from rock beds. Controls depend on the use of the secondary space. Movable insulation is used on the collector at night if the space is lived in or if the space is used to distribute heat by convection to the main house. Otherwise, night insulation is sometimes used on glazed areas between the secondary space and the main living spaces. Summer shading and ventilation are particularly important controls. With minimal adjustments, the secondary space can often be used to drive a convective ventilation system that cools the entire house. Reference system parameters used in the analysis are listed in Figure 5-7 (16,23,24,25).
### Figure 5-7

**Standardized Values of Greenhouse Systems Considered**

<table>
<thead>
<tr>
<th>Solar Aperture</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of glazings</td>
<td>2</td>
</tr>
<tr>
<td>Glass transmissivity (at normal incidence)</td>
<td>0.747</td>
</tr>
<tr>
<td>Orientation</td>
<td>Vertical and south facing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Thermal Storage</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal storage</td>
<td>45 BTU/°F·ft²</td>
</tr>
<tr>
<td>Building Mass</td>
<td>Negligible</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.0 BTU/ft·hr·°F</td>
</tr>
<tr>
<td>Heat Capacity</td>
<td>30 BTU/ft³·°F</td>
</tr>
<tr>
<td>Wall Absorptance</td>
<td>1.0</td>
</tr>
</tbody>
</table>

| Air Temperature Range in Building | 65°F to 75°F |
| Night Insulation (if used) | R9 Insulation in place from 5 p.m. to 7 a.m. |
| Wall to Room Air Conductance | 1.0 BTU/hr·°F·ft² |
| Ground Reflectance | 0.3 |
| No shadings |  |

**5-12**
SECTION 6.0
SOLAR SYSTEMS ANALYSIS

6.1 Summary

Performance of passive and utility-interactive PV systems without storage was calculated for 1978 and 1986 residences in Boston, Nashville, and Phoenix. These simulations were based on the passive system specifications defined in Section 5.2, and the PV system specifications defined in Section 5.3. The code used to perform the simulation of passive and PV systems was developed from three primary sources (19,23,26).

Simulation inputs included: base appliance and domestic hot water loads discussed in Section 4.2; space heating demands discussed in Section 4.3; and, weather data discussed in Section 3.3. Space heating demands in Section 4.3, which are normalized for floor area and heating degree days, were scaled to a 139.4 m² (1500 ft²) residence in each city for ease of evaluation and presentation.

Simulation of direct gain, Trombe wall, and sunspace systems focused on passive savings under 30% and over 60% of the space heating envelope demand for residences in 1978 and 1986. Nomographs were prepared to expand the applicability of data from these points over a broad range of annual daytime electrical loads. PV system array areas investigated ranged from 50 m² to 90 m².

Electrical loads for monthly daytime heating were calculated for 1978 and 1986 levels of envelope conservation with suntempering (i.e., less than 30% savings in heating demand). It was found that daytime heating accounted for 14% to 24% of the total (24 hr.) electrical load for heating. When the passive savings in heating demand was increased to more than 60% of the total (24 hr.) demand, no significant change occurred in the daytime total electric load.

Doubling the amount of passive savings in heating demand from under 30% to more than 60%, reduced the 24 hr. electrical load for heating by more than half. In addition, the daytime electrical load for heating was reduced by one-half to three-fourths in 1978 and 1986 residences.
Passive heating contributions reduce interaction of the PV system with the load. Similarly, reduction in energy use from 1978 levels to those expected in 1986 also contribute to reduce PV system/electrical load interaction. Small differences in displaced utility electricity and PV system output sold back at the under-30% and over 60% levels of passive contribution indicate the PV system's relative insensitivity to large amounts of passive solar heating. This is due to the fact that the PV system does not see the various electrical loads from appliances, DHW or heating separately, but only as total (24 hr.) electrical load. When daytime heating has been achieved through suntemp­pering (30% passive contribution) daytime electrical heating demand drops to a minimal portion of the total electric load. It follows that further reductions of the electrical heating load (i.e., increasing passive contribution) would have minimal impact upon PV system interaction.

Load and system performance for energy-conserving 1986 residences with less than 30% passive contribution are equivalent to values for the prototypes developed by GE and Westinghouse, once weather data, residence size, and PV system efficiency are normalized. This indicates that even if the prototypes had been developed with more than a 60% passive heating savings in demand, no significant differences from the performance predictions previously reported would occur.

6.2 Passive System Performance

Passive system performance was determined using the system specifications defined in Section 5.2 for south-facing glazing areas that yielded heating demand savings under 30% and over 60%. Calculation of solar input was made from the product of available insolation, aperture area, transmittance and absorptance. The generic formula used in the calculation is shown below:

\[ Q = W \times I \times T \times S \]

Collected heat is represented by \( Q \), in kWh/day. Aperture area is given for \( W \), in m\(^2\), and insolation for south-facing orientation and vertical tilt conditions is given for \( I \), in kWh/m\(^2\)-day. Transmittance is given for \( T \), and absorptance is given for \( S \).

Heating demands for a 139.4 m\(^2\) (1500 ft\(^2\)) residence in Boston, Nashville and Phoenix were scaled from those developed in Section 4.3 for typical values of energy consumption in 1978 and 1986. The ratio of monthly solar radiation collected to monthly heating demands was calculated. Then the fraction of heating demand satisfied by the passive system was approximated using
exponential curve fits of hourly data reported in Reference 23 for direct, indirect and isolated gain systems. The formulae used in the calculation are shown below (23,24,25).

**Direct Gain:**

\[
SF = 0.5420 \times R, \quad R < 0.7 \\
= 0.9866 - 1.1479 \times \exp(-0.9097 \times R), \quad R > 0.7
\]

**Trombe Wall:**

\[
SF = 0.4556 \times R, \quad R < 1.0 \\
= 0.9769 - 1.2.58 \times \exp(-0.8469 \times R), \quad R > 1.0
\]

**Sunspace:**

\[
SF = 0.4846 \times R, \quad R < 1.2 \\
= 0.9799 - 1.8495 \times \exp(-1.279 \times R), \quad R > 1.2
\]

The fraction of heating demand satisfied by the passive system is denoted by SF. The ratio of monthly solar radiation collected to monthly heating demands is represented by R. The heating demand met by the heat pump, HDA, was determined from the following relationship between envelope heating demand, HD, and solar savings fraction, SF:

\[
HDA = HD \times (1 - SF)
\]

The heating electrical load, HL, was determined from the following relationship between envelope heating demand, HDA, and the coefficient of performance, COP, of the heat pump and electric resistance back-up (12,14,27):

\[
HL = \frac{HDA}{COP}
\]

The monthly average daytime heating electrical load interacts with the PV system. Daytime loads reflect the effect of each site's diurnal temperature swing. When these loads were calculated for 1978 and 1986 levels of envelope conservation with suntempering, they showed that daytime heating accounted for 14% to 24% of the total (24 hr.) heating load. When the passive savings in heating demand was increased to more than 60% of the total (24 hr.) heating demand, no significant change occurred in the daytime total electric load. Table 6-1 lists heating demand and heating load for 139.4 m² (1500 ft²) residences in 1978. For these residences, doubling the amount of passive savings in heating demand from under 30% to more than 60%, reduced the daily (24 hr.) heating load by more than half, reduced the daytime heating load by one-half to three-fourths, but did not significantly reduce the total daytime electrical load.
### TABLE 6-1. 1978 HEATING DEMAND (MWh/yr) AND HEATING ELECTRICAL LOAD (MWh/yr)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SOLAR PCT.</th>
<th>HTG. DEMAND</th>
<th>HTG. ELEC. LOAD</th>
<th>TOTAL ELEC. LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BLDG.</td>
<td>AUX.</td>
<td>DAILY</td>
</tr>
<tr>
<td>BOSTON</td>
<td>27.5</td>
<td>25.25</td>
<td></td>
<td>5.80</td>
</tr>
<tr>
<td></td>
<td>64.7</td>
<td>25.25</td>
<td>8.92</td>
<td>2.78</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>28.1</td>
<td>14.60</td>
<td>10.50</td>
<td>3.22</td>
</tr>
<tr>
<td></td>
<td>70.4</td>
<td>14.60</td>
<td>4.32</td>
<td>1.32</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>28.4</td>
<td>5.78</td>
<td>4.14</td>
<td>1.22</td>
</tr>
<tr>
<td></td>
<td>65.4</td>
<td>5.78</td>
<td>2.00</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Table 6-2 lists heating demand and heating electrical load for 139.4 m² (1500 ft²) residences in 1986. Similar to the 1978 residences, doubling the amount of passive savings in heating demand from under 30% to more than 60% reduced the daily 24 hr. heating load by more than half, reduced the daytime heating load by one-half to three-fourths, but did not significantly reduce the total daytime electric load.

### TABLE 6-2. 1986 HEATING DEMAND (MWh/yr) AND HEATING ELECTRICAL LOAD (MWh/yr)

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SOLAR PCT.</th>
<th>HTG. DEMAND</th>
<th>HTG. ELEC. LOAD</th>
<th>TOTAL ELEC. LOAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>BLDG.</td>
<td>AUX.</td>
<td>DAILY</td>
</tr>
<tr>
<td>BOSTON</td>
<td>27.5</td>
<td>12.63</td>
<td>9.15</td>
<td>2.90</td>
</tr>
<tr>
<td></td>
<td>64.7</td>
<td>12.63</td>
<td>4.46</td>
<td>1.39</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>28.1</td>
<td>7.30</td>
<td>5.25</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>70.4</td>
<td>7.30</td>
<td>2.16</td>
<td>0.66</td>
</tr>
<tr>
<td>PHOENIX</td>
<td>28.4</td>
<td>2.89</td>
<td>2.07</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>65.4</td>
<td>2.89</td>
<td>1.00</td>
<td>0.29</td>
</tr>
</tbody>
</table>
6.3 PV System Performance

PV system output was determined based on the system specifications defined in Section 5.3 for array areas between 50 m² and 90 m². Calculation of system output was made from the product of available insolation, array area and system efficiency. System efficiency, in turn, was determined from the product of cell area, wiring and inverter efficiencies. The generic formula used in the calculation is shown below (3,4,19).

\[ P = A \times N \times I \]

where \( N = \prod_{j} \eta_j \)

System output is represented by \( P \), in kWh/day. Array is given for \( A \), in m², and insolation for south-facing orientation and latitude - 10% tilt conditions is given for \( I \), in kWh/m²-day. The product of temperature-corrected efficiencies is represented by \( N \). Table 6-3 lists system output determined for various array areas in each case study location.

**TABLE 6-3. ANNUAL SYSTEM OUTPUT (MWh/YR)**

<table>
<thead>
<tr>
<th>ARRAY AREA (in M²)</th>
<th>BOSTON</th>
<th>NASHVILLE</th>
<th>PHOENIX</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5.91</td>
<td>7.13</td>
<td>9.68</td>
</tr>
<tr>
<td>60</td>
<td>7.09</td>
<td>8.57</td>
<td>11.63</td>
</tr>
<tr>
<td>70</td>
<td>8.27</td>
<td>11.43</td>
<td>13.58</td>
</tr>
<tr>
<td>80</td>
<td>9.45</td>
<td>12.87</td>
<td>15.53</td>
</tr>
<tr>
<td>90</td>
<td>10.63</td>
<td></td>
<td>17.48</td>
</tr>
</tbody>
</table>

Daytime loads discussed in Section 6.2, together with PV system output were used to determine the amount of utility generated electricity displaced. First, the ratio of monthly average daytime load to monthly average daily PV system output was calculated. Then the fraction of PV system output supplied to the load was approximated using a quadratic curve fit of hourly data reported in Reference 3. The formula used in the calculation is shown below.

\[ DF = C_0 + (C_1 \times R) - (C_2 \times R^2) \]
This monthly average fraction is represented by DF. The ratio of daytime load to daily PV system output is represented by R, and the regression coefficients by CO, CI, and C2. The utility supplied electricity displaced by the PV system's output was determined from the following relationship:

\[ DE = P \times DF \]

Displaced electricity from the grid is represented by DE, in kWh/day.

It was assumed that PV system output not supplied directly to on-site residential loads was sold to the grid. The relationship between PV system output, P, displaced utility energy, DE, and sellback energy, SE, is shown below:

\[ SE = P - DE \]

Tables 6-4 and 6-5 show utility energy and sellback energy from a 50 m² array PV system for passive savings under 30% and over 60% of the heating demand. These values were based on loads scaled for 139.4 m² (1500 ft²) residences in Boston, Nashville and Phoenix for the 1978 and 1986 periods.

**TABLE 6-4. ANNUAL PERFORMANCE (MWh/YR) of a 50M² ARRAY PV SYSTEM IN 1978**

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Under 30% Passive Savings</th>
<th>Over 60% Passive Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electric Load</td>
<td>PV System</td>
</tr>
<tr>
<td></td>
<td>Total   Day</td>
<td>Direct</td>
</tr>
<tr>
<td>BOSTON</td>
<td>19.20   9.70</td>
<td>4.46</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>14.44   8.10</td>
<td>4.37</td>
</tr>
</tbody>
</table>
The tables show that passive heating contributions reduce interaction of the PV system with the load. Similarly, energy conservation reduction from 1978 values to those expected in 1986 also contribute to reduce interaction of the PV system with the load. The interactive effect resulting from this passive contribution is more significant where the heating load is a major factor in the total load.

PV system/on-site load interaction is reduced by 9% in Boston and 7% in Nashville when the passive fraction of the heating demand is increased from below 0.30 to more than 0.60 for a 50 m² array PV system and a 139.4 m² (1500 ft²) residence in 1978. Comparable values for the same size PV system and the same size residence in 1986 are 7% in Boston and 2% in Nashville. No significant difference occurs in either 1978 or 1986 for the Phoenix cases.

TABLE 6-5. ANNUAL PERFORMANCE (MWh/yr) OF A 50M² ARRAY PV SYSTEM IN 1986

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Under 30% Passive Savings</th>
<th>Over 60% Passive Savings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Electric Load</td>
<td>PV System</td>
</tr>
<tr>
<td></td>
<td>Total Day Direct Sold</td>
<td></td>
</tr>
<tr>
<td>BOSTON</td>
<td>14.79 8.04 4.09 1.82</td>
<td>13.31 7.59 3.97 1.94</td>
</tr>
<tr>
<td>NASHVILLE</td>
<td>12.75 7.15 4.03 3.10</td>
<td>11.78 6.80 3.98 3.15</td>
</tr>
<tr>
<td>Phoenix</td>
<td>11.71 6.95 4.46 5.22</td>
<td>11.39 6.90 4.47 5.21</td>
</tr>
</tbody>
</table>

Small differences in displaced utility electricity and PV system output sold at the under-30% and over-60% level of passive contribution indicate the PV system's relative insensitivity to large amounts of passive solar heating. Once daytime heating has been achieved through suntempering, (30% passive contribution) daytime electrical heating demand drops to a minimal portion of the total electric load. It follows that further reductions of the electrical heating load (i.e., increasing passive contribution) would have minimal impact upon the total daytime electric load.
Load and system performance values shown for the 1986 residences with less than a 30% passive contribution are equivalent to those for prototypes developed by GE and Westinghouse, once weather conditions, residence size, and system efficiency are normalized. This data indicates that even if the prototypes had been developed with more than 60% passive heating contribution, no significant differences from performance predictions previously reported would occur.

A set of nomographs and tables were developed for Boston, Nashville and Phoenix using the source code listed in Section 8.0. These tools were developed to permit comparison of displaced utility energy over a broader range of daytime loads and system sizes than those discussed above. After monthly values of daytime load and PV system output were prepared, an exponential curve fit of annual data was performed to bracket system sizes using areas between 50 m² and 90 m². The correlation coefficient, in all cases more than 0.98, indicated a close fit. Then the performance of systems at 10 m² increments in array area were interpolated and plotted (28).

Daytime loads, system sizes expressed as array areas and system output, and displaced utility energy are listed in Table 6-6 for Boston, Table 6-7 for Nashville, and Table 6-8 for Phoenix. Values other than those listed may be interpolated for daytime load and system sizes of interest. Nomographs are illustrated in Figure 6-1 for Boston, Figure 6-2 for Nashville, and Figure 6-3 for Phoenix. In each nomograph, the values for 1978 and 1986 residences with less than 30% and more than 60% passive solar savings listed in Tables 6-4 and 6-5 are shown.
A - Annual 1986 Performance with over 60% passive savings in space conditioning load.

B - Annual 1986 Performance with under 30% passive savings in space conditioning load.

C - Annual 1978 Performance with over 60% passive savings in space conditioning load.

D - Annual 1978 Performance with under 30% passive savings in space conditioning load.

TABLE 6-6. BOSTON PERFORMANCE TABLE

<table>
<thead>
<tr>
<th>Daytime Load (MWh/Yr)</th>
<th>Displaced Electricity (MWh/Yr) for System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AREA (M^2) 50 60 70 80 90 OUTPUT (MWh/Yr)</td>
</tr>
<tr>
<td></td>
<td>5.91 7.09 8.27 9.45 10.63</td>
</tr>
<tr>
<td>7</td>
<td>3.85 4.00 4.15 4.30 4.45</td>
</tr>
<tr>
<td>8</td>
<td>4.11 4.30 4.49 4.69 4.88</td>
</tr>
<tr>
<td>9</td>
<td>4.36 4.59 4.83 5.06 5.29</td>
</tr>
<tr>
<td>10</td>
<td>4.59 4.87 5.14 5.42 5.70</td>
</tr>
</tbody>
</table>
A - Annual 1986 Performance with over 60% passive savings in space conditioning load.

B - Annual 1986 Performance with under 30% passive savings in space conditioning load.

C - Annual 1978 Performance with over 60% passive savings in space conditioning load.

D - Annual 1978 Performance with under 30% passive savings in space conditioning load.

TABLE 6-7. NASHVILLE PERFORMANCE TABLE

<table>
<thead>
<tr>
<th>Daytime Load (MWh/Yr)</th>
<th>Displaced Electricity (MWh/Yr) for System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (m²) 50 60 70 80 90 OUTPUT (MWh/Yr) 7.13 8.57 10.00 11.43 12.87</td>
</tr>
<tr>
<td>6</td>
<td>3.65 3.76 3.87 3.97 4.08</td>
</tr>
<tr>
<td>7</td>
<td>4.00 4.14 4.28 4.42 4.57</td>
</tr>
<tr>
<td>8</td>
<td>4.33 4.50 4.68 4.86 5.04</td>
</tr>
<tr>
<td>9</td>
<td>4.64 4.85 5.07 5.28 5.49</td>
</tr>
<tr>
<td>10</td>
<td>4.93 5.18 5.43 5.69 5.94</td>
</tr>
</tbody>
</table>
FIGURE 6-3. PHOENIX PERFORMANCE NOMOGRAPH

A - Annual 1986 Performance with over 60% passive savings in space conditioning load.
B - Annual 1986 Performance with under 30% passive savings in space conditioning load.
C - Annual 1978 Performance with over 60% passive savings in space conditioning load.
D - Annual 1979 Performance with under 30% passive savings in space conditioning load.

TABLE 6-7. PHOENIX PERFORMANCE TABLE

<table>
<thead>
<tr>
<th>Daytime Load (MWh/Yr)</th>
<th>Displaced Electricity (MWh/Yr) for System Size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AREA (M²) 50  60  70  80  90</td>
</tr>
<tr>
<td></td>
<td>OUTPUT (MWh/YR) 9.68 11.53 13.58 15.53 17.48</td>
</tr>
<tr>
<td>6</td>
<td>3.96 4.04 4.11 4.19 4.26</td>
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<td>4.99 5.13 5.26 5.40 5.53</td>
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<tr>
<td>9</td>
<td>5.50 5.66 5.82 5.98 6.15</td>
</tr>
<tr>
<td>10</td>
<td>5.99 6.18 6.37 6.57 6.76</td>
</tr>
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</table>
SECTION 7.0

REFERENCES


SECTION 8.0

APPENDIX

8.1 Summary

A computer code was developed to simulate the performance of utility interactive PV systems with passive heating systems for Boston, Nashville and Phoenix. The cost is based on the methods described in References (23) and (19).

Solar radiation input values are based on the Liu-Jordan correlation with KT. Temperature and degree-day values were obtained from Reference 23. Passive system contribution is calculated using the Solar Load Ratio (SLR) correlation (23). Heat pump loads are calculated using the performance characteristics described in Section 4.3. PV system displacement of utility generated electricity is calculated using the Demand Solar Ratio (DSR) correlation (19).

The code, written in BASIC, has been implemented on a Wang System 2200. Approximately 30k bytes is required for program operation. A listing of the code follows. A sample input summary is illustrated in Figure 8-1. A sample output summary is illustrated in Figure 8-2.
10REM ****************************AIA RESEARCH CORPORATION****************************
20REM * PV/PASSIVE RESIDENTIAL MODEL 1.0  *
30REM ****************************PROGRAM ESTIMATES THE PERFORMANCE AND LIFE ********************
40REM **CYCLE COST FOR A UTILITY INTERACTIVE PV SYSTEM WITHOUT STORAGE IN A PASSIVE-SOLAR/ALL-ELECTRIC RESIDENCE.**
50REM ****************************
60REM THIS PROGRAM ESTIMATES THE PERFORMANCE AND LIFE  
70REM STORAGE IN A PASSIVE-SOLAR/ALL-ELECTRIC RESIDENCE.  
80REM ****************************
90DIM M(12),O(12),X(12),F(12),S(12),U(12),B(12)
100DIM Q1(12),Q2(12),D1(12),D2(12),S1(12),T1(12),T2(12)
110DIM T3(12),C1(12),C2(12),C3(12),F1(12),F2(12),F3(12)
120DIM Q3(12),T4(12),T5(12),T6(12),C4(12),F4(12),F5(12)
130DIM L1(12),L2(12),L3(12),H1(12),H2(12),L4(12),L5(12)
140DIM D3(12),P1(12),P2(12),P3(12),P4(12),H3(12),H4(12)
150DIM P5(12),P6(12),M(12),D4(12),D5(12),D6(12)
160GOSUB 2930
170PRINT HEX(03)
180FOR I=1TO 12
190Q(I),X(I),F(I),S(I),U(I),B(I)=O
200Q1(I),Q2(I),D1(I),D2(I),S1(I),T1(I),T2(I)=O
210T3(I),C1(I),C2(I),C3(I),F1(I),F2(I),F3(I)=O
220Q3(I),T4(I),T5(I),T6(I),C4(I),F4(I),F5(I)=O
230L1(I),L2(I),L3(I),H1(I),H2(I),L4(I),L5(I)=O
240D3(I),P1(I),P2(I),P3(I),P4(I),H3(I),H4(I)=O
250P5(I),P6(I),D4(I),D5(I),D6(I)=O
260NEXT I
270PRINT "PV SYSTEM PERFORMANCE/COST ESTIMATION"
280PRINT "ENTER CITY CODE FOR WEATHER DATA"
290INPUT C
300ON CB GOSUB 3350,3480,3610
310PRINT "THE CODES IN THE PERFORMANCE MODULE ARE:
320PRINT "1.LOAD INPUTS"
330PRINT "2.SYSTEM INPUTS"
340PRINT "3.SYSTEM OUTPUT"
570 PRINT "**********************************************************************************"
580 INPUT "WHICH CODE DO YOU WISH TO USE", k1
590 ON k1 GOSUB 610, 1450, 1670, 1810
600 GOTO 510
610 REM *************************************************************************************
620 INPUT "ENTER DAILY D/H/W LOAD", C3
630 INPUT "ENTER DAILY BASE LOAD", C2
640 C4(12), C4(1), C4(2)=1.18*C2
650 C4(3), C4(4), C4(5)=.94*C2
660 C4(6); C4(7); C4(8)=.86*C2
670 C4(9); C4(10); C4(11)=1.03*C2
680 L6, L7=0
690 FOR I=1 TO 12
700 L4(I)=M(I)*(C3)
710 L5(I)=M(I)*C4(I)
720 L2(I)=L4(I)+L5(I)
730 L3(I)= (.722*C3)+(.525*C4(I))
740 L6=L6+L4(I)
750 L7=L7+L5(I)
760 NEXT I
770 PRINT "ENTER CODE FOR PASSIVE SYSTEM TYPE"
780 PRINT "(1)DIRECT GAIN""
790 PRINT "(2)TROMBE WALL"
800 PRINT "(3)SUNSPACE"
810 INPUT C9
820 ON C9 GOSUB 2990, 3070, 3150
830 INPUT "ENTER BUILDING 'UA'(BTU/H-F)", C5
840 D4=0
850 FOR I=1 TO 12
860 D4=D4+D1(I)
870 NEXT I
880 C7=C5*24
890 INPUT "ENTER SOUTH-FACING GLAZING AREA(FT2)", C6
900 C=C7/C6
910 K=1+(G/C)
920 FOR I=1 TO 12
930 Q(I)=Q1(I)*M(I)*A*T
940 B(I)=C7*D1(I)
950 Q3(I)=Q1(I)*A*T
960 T5(I)=T2(I)+5+(Q3(I)/C)
970 NEXT I
980 FOR I=1 TO 12
990 IF D1(I)<0 THEN 1010
1000 D1(I)=.1
1010 X(I)=(Q(I)/D1(I))/C*K
1020 IF X(I)>R THEN 1050
1030 ON C9 GOSUB 3020, 3100, 3180
1040 GOTO 1060
1050 ON C9 GOSUB 3040, 3120, 3200
1060 S(I)=1-(K*(1-F(I)))
1070 U(I)=B(I)*(1-S(I))
1080 NEXT I
1090 FOR I=1 TO 12
1100 H2(I)=0
1110 FOR J=6 TO 19
1120 IF C9>1 THEN 1150

8-3
1130 T8=TS(I)+TS(I)*(W1/2)*(SIN(2*PI*(22-J)/24))
1140 GOTO 1160
1150 T8=TS(I)+TS(I)*(W1/2)*(SIN(2*PI*(24-J)/24))
1160 T7=T2(I)+((T3(I)-T1(I))/2)*(SIN(2*PI*(20-J)/24))
1170 IF (6S-T8)<0 THEN 1200
1180 IF (T8-T7)<0 THEN 1200
1190 H2(I)=H2(I)+C5*(T8-T7)
1200 NEXT I
1210 NEXT J
1220 FOR I=1 TO 12
1230 H4(I)=0
1240 H3(I)=C5*24*D2(I)
1250 FOR J=6 TO 19
1260 T7=T2(I)+((T3(I)-T1(I))/2)*(SIN(2*PI*(20-J)/24))
1270 IF (T7-6S)<0 THEN 1290
1280 H4(I)=H4(I)+C5*(T7-6S)
1290 NEXT J
1300 NEXT I
1310 FOR I=1 TO 12
1320 T7=T2(I)
1330 IF T7>68 THEN 1360
1340 M3=2.126*T7+.1081
1350 GOTO 1370
1360 M3=M3+1685.5*T7*(1.405)
1370 F2(I)=(H(I)/M3)/3413
1380 F3(I)=(H2(I)/M3)/3413
1390 F4(I)=(H3(I)/M3)/3413
1400 F5(I)=(H4(I)/M3)/3413
1410 L2(I)=L2(I)+F2(I)+F4(I)
1420 L3(I)=L3(I)+F3(I)+F5(I)
1430 NEXT I
1440 RETURN
1450 REM **********PV SYSTEM INPUT ROUTINE************
1460 INPUT "ENTER MODULE AREA", A2
1470 INPUT "ENTER NUMBER OF MODULES", M1
1480 INPUT "ENTER ENCAPSULATED CELL EFFICIENCY", E1
1490 INPUT "ENTER MODULE TEMP/EFFICIENCY COEFFICIENT", N2
1500 INPUT "ENTER REFERENCE TEMPERATURE", I7
1510 INPUT "ENTER REFERENCE INSOLATION (IN KW)", I9
1520 INPUT "ENTER MODULE TEMP/EFFICIENCY COEFFICIENT", N2
1530 INPUT "ENTER WIRING EFFICIENCY", E2
1540 INPUT "ENTER CELL PACKING DENSITY", E3
1550 INPUT "ENTER ARRAY PACKING DENSITY", E4
1560 INPUT "ENTER INVERTER EFFICIENCY", I8
1570 A1=A2*M1
1580 E5=(T9-I7)/I9
1590 FOR I=1 TO 12
1600 E6=N2*(T9-(E5+Q2(I)/S1(I))
1610 E7=({.617)*N2=E5+Q2(I)),
1620 N1=N1*(1+E6+E7)
1630 P2(I)=A1*N1*Q2(I)
1640 NEXT I
1650 RETURN
1660 RETURN
REM PV SYSTEM OUTPUT ROUTINE
FOR I=1 TO 12
D3(I)=L3(I)/P2(I)
H1(I)=C1(I)+(C2(I)*D3(I))-(C3(I)*(D3(I)^2))
IF H1(I)>0 THEN 1730
H1(I)=1
P3(I)=(1-H1(I))*P2(I)
P1(I)=L2(I)-((H1(I)*P2(I))*M(I))
L2(I)=L2(I)/1000
P4(I)=(P1(I))/1000
P5(I)=(P2(I)*M(I))/1000
P6(I)=(P3(I)*M(I))/1000
NEXT I
RETURN
GOTO 370
REM MODULE NUMBER 2
PRINT HEX(03); "*********************************************"
PRINT "THE CODES IN THE COST MODULE ARE:",K1
GOTO 1830
PRINT HEX(03); "*********************************************"
INPUT "WHICH CODE DO YOU WISH TO USE",K2
ON K2 GOSUB 2000,2010,2020,2030,2040,2050,2060,2070,2080,2090,2100,2110,2120,2130,2140,2150,2160,2170,2180,2190,2200
SELECT PRINT 005
GOTO 2020
IF K3=0 THEN 2190
SELECT PRINT 215(132)
PRINT HEX(0E); "**********************************************************
**
8-5
2200 PRINT HEX(0E);"INPUT VALUES FOR WEATHER DATA"
2210 PRINT HEX(0E);"**************************************************************************
2220 PRINT USING 2230,"MONTH","HDD","CDD","AVG.TEMP","PASOLIN","PV SOLIN"
2230######## # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
2240 FOR I=1 TO 12
2250 PRINT USING 2280,M$(I),D1(I),D2(I),T2(I),Q1(I),Q2(I)
2260 NEXT I
2270 PRINT HEX(0AOA)
2280######## # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # # #
2290 PRINT HEX(0E);"INPUT VALUES FOR PASSIVE SYSTEM"
2300 PRINT HEX(0E);"**************************************************************************
2310 PRINT "PASSIVE SYSTEM TYPE=",C3
2320 PRINT "(1)DIRECT GAIN"
2330 PRINT "(2)TROMBE WALL"
2340 PRINT "(3)SUNSPACE"
2350 PRINT "BUILDING 'UA' (BTU/H-F)=",C5
2360 PRINT "SOUTH-FACING GLAZING AREA(FT2)=",C6
2370 PRINT HEX(0AOA)
2380 PRINT HEX(0AOA)
2390 PRINT HEX(0E);"OUTPUT VALUES FOR RESIDENTIAL LOADS"
2400 PRINT HEX(0AOA)
2410 PRINT HEX(0AOA)
2420 PRINT HEX(0E);"**************************************************************************
2430 PRINT "DIRECT GAIN"
2440 PRINT "TROMBE WALL"
2450 PRINT "SUNSPACE"
2460 PRINT "BUILDING 'UA' (BTU/H-F)=",C5
2470 PRINT "SOUTH-FACING GLAZING AREA(FT2)=",C6
2480 PRINT HEX(0AOA)
2490 PRINT HEX(0AOA)
2500 PRINT HEX(0E);"**************************************************************************
2510 IF K3=0 THEN 2540
2520 PRINT HEX(0E);"**************************************************************************
2530 PRINT "DIRECT GAIN"
2540 PRINT "TROMBE WALL"
2550 PRINT "SUNSPACE"
2560 PRINT "BUILDING 'UA' (BTU/H-F)=",C5
2570 PRINT "SOUTH-FACING GLAZING AREA(FT2)=",C6
2580 PRINT "NUMBER OF MODULES=",M1
2590 PRINT "ENCAPSULATED CELL EFFICIENCY=",E1
2600 PRINT "WIRING EFFICIENCY=",E2
2610 PRINT "NOCT=",T9
2620 PRINT "MODULE TEMP/EFFICIENCY COEFFICIENT=",N2
2630 PRINT "FULL RATED PCU LOAD (IN KVA) =", M2
2640 PRINT "CELL PACKING DENSITY =", E3
2650 PRINT "ARRAY PACKING DENSITY =", E4
2660 RETURN
2670 IF K3 = 0 THEN 2690
2680 SELECT PRINT 215(132)
2690 PRINT "***********************************************************************"
2700 PRINT "INPUT VALUES FOR LIFE CYCLE COSTING"
2710 PRINT "***********************************************************************"
2720 RETURN
2730 IF K3 = 0 THEN 2750
2740 SELECT PRINT 215(132)
2750 PRINT HEX(OE); "***********************************************************************"
2760 PRINT "OUTPUT VALUES FOR SYSTEM PERFORMANCE"
2770 PRINT HEX(OE); "***********************************************************************"
2790 L
2800 FOR I = 1 TO 12
2810 PRINT USING 2830, M$(I), F3(I), F5(I), .525*C4(I), .722*C3, L
2820 NEXT I
2830 PRINT "***********************************************************************"
2840 RETURN
2850 IF K3 = 0 THEN 2870
2860 SELECT PRINT 215(132)
2870 PRINT "OUTPUT VALUES FOR LIFE CYCLE COSTING"
2880 PRINT "***********************************************************************"
2890 RETURN
2900 GOTO 370
2910 M$(1) = "JAN"; M$(2) = "FEB"; M$(3) = "MAR"; M$(4) = "APR"
2920 M$(5) = "MAY"; M$(6) = "JUN"; M$(7) = "JUL"; M$(8) = "AUG"
2930 M$(9) = "SEP"; M$(10) = "OCT"; M$(11) = "NOV"; M$(12) = "DEC"
2940 M(1) = 31; M(2) = 28; M(3) = 31; M(4) = 30; M(5) = 31; M(6) = 30
2950 M(7) = 31; M(8) = 31; M(9) = 30; M(10) = 31; M(11) = 30; M(12) = 31
2960 RETURN
2970 REM "************************************************************************
2980 A = 0.8; T = 0.747; R = 0.7; G = 2.4; W1 = .74
2990 RETURN
3000 F(I) = 0.5420*X(I)
3010 RETURN
3020 F(I) = 0.9866 - 1.1479*EXP(-.9097*X(I))
3030 RETURN
3040 REM "************************************************************************
3050 A = 0.8; T = 0.747; R = 1.0; G = 0.5; W1 = .65
3060 RETURN
3070 F(I) = 0.4556*X(I)
3080 RETURN
3090 RETURN
3100
REM ****************************TROMBE WALL****************************
REM ****************************SUNSPACE****************************
A=0.88; T=0.747; R=1.21; G=0.7; W1=.39
RETURN

REM *************SUNSPACE**********************
A=0.8; T=0.747; R=1.2; G=0.7; W1=.39
RETURN

F(I)=0.9769-1.2159*EXP(-0.8469*X(I))
RETURN

REM ****************************SUNSPACE****************************
REM ****************************WEATHER DATA MAP TABLE****************************
REM G1(J)=TOTAL DAILY VERTICAL INSOLATION (BTU/FT2)
REM G2(J)=TOTAL DAILY INSOLATION AT (LAT-10)OEG (KWH/M2)
REM C1(J)=MONTHLY DIRECT FRACTION COEFFICIENT
REM C2(J)=MONTHLY DIRECT FRACTION COEFFICIENT C1
REM C3(J)=MONTHLY DIRECT-FRACTION COEFFICIENT C2
REM 01(J)=MONTHLY HEATING DEGREE DAYS (65F)
REM 02(J)=MONTHLY COOLING DEGREE DAYS (65F)
REM T1(J) -DAILY MEAN TEMP (FOE:G)
REM T2(J)=DAILY MEAN TEMP(FDEG)
REM T3(J)=DAILY MAXIMUM TEMP(FDEG)

G1(1) =878; G1(2) =1052; G1(3) =1127; G1(4) =1030; G1(5) =944; G1(6) =940; G1(7) =940; G1(8) =1009; G1(9) =1122; G1(10) =1192; G1(11) =874; G1(12) =788
G2(1) =2.02E9; G2(2) =3.25; G2(3) =3.75; G2(4) =4.02; G2(5) =4.47; G2(6) =4.62; G2(7) =4.55; G2(8) =4.82; G2(9) =4.33; G2(10) =3.79; G2(11) =2.64; G2(12) =2.42
G3(1) =4.62; G3(2) =5.15; G3(3) =5.83; G3(4) =6.58; G3(5) =7.2; G3(6) =7.55; G3(7) =7.4; G3(8) =6.87; G3(9) =6.13; G3(10) =5.42; G3(11) =4.77; G3(12) =4.45
C1(1) =.041; C1(2) =.011; C1(3) =.023; C1(4) =.021; C1(5) =.017; C1(6) =.011; C1(7) =.013; C1(8) =.022; C1(9) =.020; C1(10) =.008; C1(11) =.041; C1(12) =.039
C2(1) =.55; C2(2) =.677; C2(3) =.647; C2(4) =.757; C2(5) =.819; C2(6) =.861; C2(7) =.843; C2(8) =.773; C2(9) =.697; C2(10) =.706; C2(11) =.572; C2(12) =.530
C3(1) =.086; C3(2) =.134; C3(3) =.121; C3(4) =.167; C3(5) =.193; C3(6) =.211; C3(7) =.203; C3(8) =.174; C3(9) =.145; C3(10) =.145; C3(11) =.093; C3(12) =.080
D1(1) =1110; D1(2) =969; D1(3) =834; D1(4) =492; D1(5) =218; D1(6) =27; D1(7) =0; D1(8) =8; D1(9) =76; D1(10) =301; D1(11) =594; D1(12) =992
D2(1) =0; D2(2) =0; D2(3) =0; D2(4) =0; D2(5) =0; D2(6) =0; D2(7) =0; D2(8) =117; D2(9) =260; D2(10) =0; D2(11) =0; D2(12) =0
DELX T1(1) =22.5; T1(2) =23.3; T1(3) =31.5; T1(4) =40.8; T1(5) =50.1; T1(6) =59.3; T1(7) =65.1; T1(8) =63.3; T1(9) =56.7; T1(10) =47.5; T1(11) =38.7; T1(12) =26.6
DELX T2(1) =22.2; T2(2) =30.4; T2(3) =38.1; T2(4) =48.6; T2(5) =58.6; T2(6) =68.2; T2(7) =73.3; T2(8) =71.3; T2(9) =64.5; T2(10) =55.4; T2(11) =45.2; T2(12) =33
DELX T3(1) =35.9; T3(2) =37.5; T3(3) =44.6; T3(4) =56.3; T3(5) =67.1; T3(6) =76.6; T3(7) =81.4; T3(8) =79.3; T3(9) =72.2; T3(10) =63.2; T3(11) =51.7; T3(12) =39.3
RETURN
### Nashville Weather Data

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### Phoenix Weather Data

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### Weather Data Summary

- **Nashville**:
  - Average G1 values: 1027, 1047, 989, 885, 8, 856, 973, 116, 1253, 1039, 854
  - Average G2 values: 2.49, 3.44, 4.32, 5.44, 5.86, 5.8, 856, 973, 1116, 1253, 1039, 854
  - Average 81 values: 4.95, 5.35, 5.87, 6.45, 6.32, 7.17, 7.07, 6.67, 6.1, 5.55, 5.07, 4.83
  - Average C1 values: 0.010, 0.006, 0.022, 0.019, 0.020, 0.019, 0.020, 0.019, 0.017, 0.018, 0.008, 0.01
  - Average C2 values: 0.671, 0.727, 0.666, 0.743, 0.775, 0.796, 0.786, 0.754, 0.707, 0.630, 0.690, 0.654
  - Average C3 values: 0.130, 0.150, 0.126, 0.160, 0.171, 0.178, 0.175, 0.164, 0.147, 0.114, 0.137
  - Average D1 values: 828, 827, 825, 824, 823, 822, 821, 820, 819, 818, 817, 816
  - Average D2 values: 38.3, 41, 43.2, 45.3, 47.4, 49.5, 51.6, 53.7, 55.8, 57.9, 59.1, 61.2
  - Average T1 values: 29, 31, 32.1, 33.1, 34, 35, 36, 37, 38, 39, 40, 41
  - Average T2 values: 39.6, 42.1, 44.6, 47.1, 49.5, 51.9, 54.4, 56.8, 59.3, 61.7, 64.1, 66.5

- **Phoenix**:
  - Average Gl values: 1472, 1589, 1552, 1388, 1211, 1128, 1059, 1186, 1482, 1643, 1561, 1419
  - Average G2 values: 4.85, 6.13, 7.01, 7.8, 8.1, 7.99, 7.17, 7.14, 7.32, 6.57, 5.47, 4.73
  - Average 81 values: 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38, 5.38
  - Average C2 values: 0.010, 0.006, 0.022, 0.019, 0.020, 0.019, 0.020, 0.019, 0.017, 0.018, 0.008, 0.01
  - Average C3 values: 0.010, 0.006, 0.022, 0.019, 0.020, 0.019, 0.020, 0.019, 0.017, 0.018, 0.008, 0.01

### Return

- **Nashville**:
  - Average values: G1 = 1027, 1047, 989, 885, 8, 856, 973, 116, 1253, 1039, 854
  - Average values: G2 = 2.49, 3.44, 4.32, 5.44, 5.86, 5.8, 856, 973, 1116, 1253, 1039, 854

- **Phoenix**:
  - Average values: G1 = 1472, 1589, 1552, 1388, 1211, 1128, 1059, 1186, 1482, 1643, 1561, 1419
  - Average values: G2 = 4.85, 6.13, 7.01, 7.8, 8.1, 7.99, 7.17, 7.14, 7.32, 6.57, 5.47, 4.73

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8-9
INPUT VALUES FOR WEATHER DATA

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INPUT VALUES FOR PASSIVE SYSTEM

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(1)DIRECT GAIN
(2)TROMBE WALL
(3)SUNSPACE

BUILDING 'UA' (BTU/H-F)= 300

SOUTH-FACING GLAZING AREA (FT2)= 240

INPUT VALUES FOR SYSTEM PERFORMANCE

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<td>Motorola, Inc. A110 Attn: Bob Hammond</td>
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