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NOVEL CONTROL SYSTEMS FOR SOLAR ASSISTED SYSTEMS THAT REDUCE ELECTRIC UTILITY PEAK LOADS

Final Report

MASTER

By
Harold G. Lorsch

September 1980

Work Performed Under Contract No. AC03-77ET20085

Franklin Research Center
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U.S. Department of Energy

Solar Energy

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NOVEL CONTROL SYSTEMS FOR SOLAR ASSISTED SYSTEMS THAT REDUCE ELECTRIC UTILITY PEAK LOADS

Final Report
September, 1980

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FOREWORD

This is the final report of a research project performed at the Franklin Research Center for the Solar Heating and Cooling Research Branch of the U.S. Department of Energy. Harold G. Lorsch was the Principal Investigator, Richard E. Crane performed all simulations for Philadelphia and the cooling calculations for the other locations, and Richard L. Oswald performed the other simulations and obtained contractors costs.

The Philadelphia Electric Company was a subcontractor with the late Joseph Pasternak acting as Task Manager, succeeded by Edward MacDonald. John Kittredge assisted in validating the simulation results and performed the diversity analysis, Sheldon Shoemaker calculated the costs given in Section 5, and William Sundermeier provided some of the cost data used in Section 6. Thomas I. Wetherington of the Florida Power Corporation and Jay Lopez of the San Diego Gas and Electric Company provided valuable assistance at no cost to the project. None of these cooperating utility companies, however, is responsible for the actual costs used and the conclusions presented in this report; full responsibility for these rests with the Franklin Research Center.

The authors of this report wish to express their appreciation to Drs. Michael Wahlig, Marlo Martin, and Mashuri Warren of the Lawrence Berkeley Laboratory who, at various times, were the technical monitors for this project. Our special thanks go to Mrs. Miriam Foster for the careful typing of many drafts of this report.

ABSTRACT

Water heating, space heating, and space cooling systems with and without solar assistance and with and without off-peak thermal storage were analyzed in Philadelphia, PA, Daytona Beach, FL, and San Diego, CA. Utility costs to serve and homeowners capital investment costs were determined for 1985 and 1995, and total annual costs were compared. Conclusions were drawn as to where and when the novel systems would be economical compared to conventional systems.

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1. EXECUTIVE SUMMARY

1.1 SCOPE

The aim of the project was to develop novel systems and control strategies that reduce peak loads on electric utilities caused by the back-up demands from solar systems used in single-family residential buildings. The project was performed by the Franklin Research Center in Philadelphia, PA; the Philadelphia Electric Company was a subcontractor for certain portions of the work. Other utilities, notably Florida Power Corporation and San Diego Gas and Electric Company, contributed information at no cost to the project.

1.2 TYPICAL HOUSE

A typical suburban single-family home expected to be built during the 1980-1995 period was defined. It has a floor area of 148 m^2 (1600 ft^2) and is insulated in accordance with best present practice. The energy requirements of this home for water heating and space heating and cooling were determined in four geographical locations: Philadelphia, PA; Daytona Beach, FL; San Diego, CA; and Columbus, OH.

1.3 HEATING AND COOLING SYSTEMS

A great variety of water heating and space conditioning systems with and without solar assistance and with and without off-peak storage* were conceptualized. Control logics for the efficient use of off-peak storage were developed. The literature was extensively reviewed to include systems chosen by other investigators. The energy performance of the best heating and air conditioning systems when installed in a typical home in different locations of the U.S. was then simulated on an hourly basis during a representative year. The results for Philadelphia, PA are summarized in Table 1-1.

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*Throughout this report, off-peak storage refers to electrically charged hot or cold water storage.

Three types of domestic water heating systems that reduce utility peak loads were identified, one electric and two solar. A large number of these types of systems are in current use, and actual operating results are available. The solar air conditioning systems considered use lithium bromide absorption chillers. Their off-peak storage is in the form of hot or chilled water. These systems have an auxiliary electric heating system to operate the absorption chiller when solar energy is not available although that is not current practice. However, if a solar air conditioning system has the usual fossil-fueled auxiliary systems, from the electric utility point of view it has no air conditioning at all. Therefore electric auxiliary energy was assumed in order to determine the effect of solar assisted systems on electric utilities.

None of the heating/cooling systems was "optimized" in a strict analytical sense. Since optimization depends on fuel cost (which is different for each location and for each utility) and on the control strategy employed with each system, no two systems would have been alike if each were truly optimized. Thus, comparisons between systems and between locations would have been difficult, if not impossible, to make. Each system at each location was therefore sized for best performance based on the experience of solar installations that have actually been erected in those locations. While this does not result in a mathematical optimum, it results in systems which are close to that. Since the change in cost or energy performance of a solar system sized close to the optimum is small, the performance of the selected systems differs only slightly from the optimum.

1.4 CONTROLLERS

There is little question about the fact that proportional controllers can, indeed, improve the energy performance of solar systems. However,

Table 1-1. Annual Performance of Space Heating Systems in Philadelphia, PA

SYSTEM	TOTAL ANNUAL ELECTRICAL ENERGY CONSUMPTION (GJ)	ELECTRICAL POWER DEMAND DURING PEAK HEATING LOAD (kW)	REDUCTION IN PEAK COMPARED TO RESISTANCE (%)	SOLAR ENERGY DELIVERED TO STORAGE (GJ)	COLLECTION EFFICIENCY (%)	AUXILIARY ENERGY INPUT TO STORAGE (GJ)	ENERGY LOST FROM STORAGE (GJ)	STORAGE EFFICIENCY (%)	AUXILIARY ENERGY INTO SEPARATE STORAGE (GJ)	ENERGY LOST FROM SEPARATE STORAGE (GJ)	SEPARATE STORAGE EFFICIENCY (%)
Resistance Heating	64	8.66	0		—	—	—	—	—	—	—
Resistance W/Off-Peak Storage	74	0.13	99	—	—	72	6.7	91	—	—	—
Conventional Solar	37	8.66	0	31	23	—	4.8	84	—	—	—
Solar W/Off-Peak in Solar Storage Tank	77	0.13	99	0	0	77	13	83	—	—	—
Solar W/Separate Off-Peak Storage	47	0.13	99	31	23	—	4.9	84	44	5.9	87
Conventional Air to Air Heat Pump	27	6.69	23	—	—	—	—	—	—	—	—
Heat Pump W/Off-Peak Storage	41	3.78	56	—	—	19	5.1	73	—	—	—
Solar Assisted Heat Pump	33	8.66	0	36	27	—	4.3	88	—	—	—
Solar Assisted Heat Pump W/Off-Peak in Solar Storage Tank	40	3.42	61	28	21	17	5.3	89	—	—	—
Solar Assisted Dual Source Heat Pump W/Direct Heating from Solar	20	6.69	23	40	30	—	3.8	91	—	—	—
Solar Assisted Dual Source Heat Pump W/Direct Heating and Off-Peak in Solar Storage Tank	24	3.77	56	30	23	3.1	5.0	85	—	—	—
Solar Assisted Dual Source Heat Pump W/Direct Heating and a Separate Off-Peak Tank	25	3.06	65	34	26	—	4.5	87	7	2.7	61

in many cases, this improvement may not be justified because of the significant increase in controller cost and complexity compared to a marginal increase in the solar energy collected.

Since the purpose of the present project was not to optimize control systems per se, but to optimize the interaction between solar systems and electric utilities, no effort was devoted to optimizing controllers as such; only on-off control modes were considered. If improved proportional or other controllers are developed and introduced in the marketplace, the results presented here will not be materially affected, since they are concerned with the macro effects on utilities and not with the micro effects of decreasing the energy consumption of a solar system by a few percent.

1.5 CONTROL STRATEGIES

Four different strategies that can be employed in charging thermal energy storage during off-peak periods are listed in Table 1-2.

Method A is easy to implement. Method B requires a somewhat more sophisticated control because a certain amount of predictive capability is needed. This applies to strategies (C) and (D) to a much greater extent. It would be most efficient to have the electric utility supply the predictive data, because the data requirements exceed the capability available to the average homeowner. For example, the utility could send out a signal at the beginning of the off-peak period which would direct the storage device to be charged to the amount required. The technology to achieve this by either radio control or ripple control is available.

An alternate method of prediction could be provided by the U.S. Weather Service. The required information could be broadcast over radio and TV with the 10 pm or 11 pm news and weather report. For example, the announcer could say: "Turn your off-peak storage to number 16". This would make the control cheaper, but the homeowner would now be required to turn a dial to the indicated setting.

Table 1-2. Control Methodology Summary

Method	Type	Behavior
A	Storage device fully recharged with backup energy during every off-peak period.	Causes high standby losses. With proper sizing, avoids all on-peak power demands.
B	Storage device recharged during off-peak period to a level required to satisfy maximum demand during subsequent on-peak period.	Slightly lower standby losses. Avoids on-peak demands.
C	Storage device recharged during the off-peak period to a level sufficient to satisfy demand during subsequent on-peak period based on expected temperatures during that period.	Smaller standby losses than for strategy (B). No on-peak demands.
D	Storage device recharged during off-peak period to a level sufficient to satisfy demand during subsequent on-peak period based on expected temperatures and solar collection during that period	Smallest standby losses. No on-peak demand.

In order to determine the feasibility of using weather predictions made on the previous evening as an indication of the thermal storage requirements for the following day, attempts were made to determine the accuracy of the U.S. Weather Bureau and private forecasting services in predicting the weather, in particular the ambient temperature, twelve to fifteen hours in advance, but none of the agencies had these statistics readily available. The possibility of using the 11 pm or 12 pm temperatures as an indication of the temperature for the following day was investigated. While these temperatures were good predictors in many cases, they were siginficantly off on certain occasions, by as much as 11°C. A simplified approach was used to predict the weather. Specifically, off-peak storage charging requirements were determined as a function of the temperature at 12 pm minus 11°C. This approach was used for space heating systems with high temperature off-peak storage. The approach is somewhat conservative but ensures that off-peak storage will be sufficiently charged to meet the entire heating demand during the following on-peak period.

Off-peak recharging of storage devices can lead to secondary utility peaks at the beginning of the off-peak period. This has already happened in West Germany in parts of which off-peak service is now available to every other customer only. It is, however, relatively easy to enable the utility to manage off-peak loads in a manner that this does not occur. A simple set of load management strategies is indicated in Figure 1-1. It illustrates the differences in methods (B) and (C) of Table 1-2. It also shows that simple controls can be incorporated in the off-peak storage device which permit it to be charged either at the beginning of the charge period, or at the end of the charge period or, at a reduced rate, throughout the full duration of off-peak period. Controllers for all of the charging strategies shown are considered to be state-of-the-art.

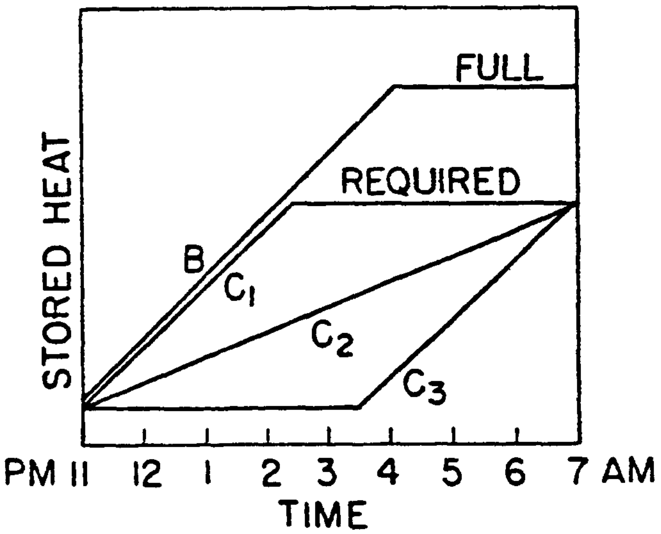

Figure 1-1. Strategies for Recharging Off-Peak Storage

1.6 UTILITY COSTS

Data for the six best heating and four best air conditioning systems were transmitted to the Philadelphia Electric Company (PECo). The personnel of that utility then compared the results with measured results on homes equipped with some of these systems on their network, validated the results, and performed a diversity analysis on these systems. The costs to serve these systems were then calculated using 1979/1980 PECo cost allocation values assuming full penetration of solar and off-peak systems, respectively.

It was not possible to obtain similarly detailed cost component breakdowns for the other cooperating utilities; therefore, their costs were calculated by Franklin personnel using best available financial data and the latest off-peak tariffs. It is believed that this procedure gives reasonably valid data.

Utility costs and consumer costs were added to determine the most desirable systems from the point of society. The former consist of capital investment for generation, transmission, distribution, metering (if required), and operating costs (mostly fuel); the latter consist of capital costs for system installation and any differences in repair and maintenance costs between conventional and new systems. This method has the advantage of not requiring any consideration of electric tariffs. Tariffs to induce desirable consumer actions and to reimburse utilities for their costs to serve these consumers should be the subject of a subsequent study.

A marginal costs cost analysis was also performed for five selected heating systems in Philadelphia. Their diversified loads were incorporated in the PECo total load model on an hour-by-hour basis throughout the year. Based on the generation mix planned for 1985 and 1995 and using economic dispatch of all units, total fuel costs were determined, and the fuel cost avoidance due to the presence of solar residential heating was evaluated.

1.7 RECAPITULATION

The effects of using all-electric water heating and space conditioning systems with and without solar assistance and with and without off-peak storage were evaluated. Energy consumption, peak electrical loads, utility costs to serve, and homeowner capital costs were determined in various locations of the country for summer peaking and winter peaking utilities having different generation and demand patterns. Systems were rated based on total costs: utility cost to serve plus the homeowner's cost to install the system assuming it is financed by a 12% mortgage amortizable over 20 years. Electric tariffs were not considered since they are costs internal to the "utility plus homeowner" system, and it was desired to determine what systems would be best for society as a whole. Tax considerations were not considered for the same reasons.

Costs were determined for the years 1985 and 1995 in order to identify trends. Utility costs were obtained from the cooperating utilities or, where these costs were not available, they were calculated using published financial data. Equipment costs were obtained from manufacturers and from published estimating manuals. A summary of major findings is presented in Table 1-3.

1.8 CONCLUSIONS

1. The use of off-peak storage in residential space conditioning systems is effective in reducing on-peak demands of those homes to nominal values which are required to power pumps and fans. Table 1-1 shows the energy performance of a large number of such systems for Philadelphia, PA.
2. The technology exists for the large-scale application of off-peak storage exists. Both storage devices and controllers are commercially available.

Table 1-3. Relative Effects of Adding Different Systems Components on Energy Consumption and Costs, Calculated at Three U.S. Locations

Comparison	Item	Percentage Changes** at: Philadelphia, PA	Daytona Beach, FL	San Diego, CA
Adding off-peak storage to electric water heating	Energy Consumption	+	+5	
	Cost to serve	-	-64/-55	
	Total cost	+0	-50±	
Adding off-peak storage to solar water heating	Energy Consumption		+9	
	Cost to serve		-62/-43	
	Total cost		-16	
Adding off-peak storage to electric resistance space heating	Energy Consumption	+16	+9	+10
	Cost to serve	-	-49	-50
	Total cost	+	-13/-24	+12/0
Solar heating compared to resistance heating	Energy Consumption	-42	-14	-61*
	Cost to serve	-17	-7	-43*
	Total cost	+115	+39/+24	+28/+14*
Adding off-peak storage to solar heating	Energy Consumption	+27	+9	+10*
	Cost to serve	-20/-24	-50	-50*
	Total cost	+11/+8	-13/-24	±0 *
Solar heating & A/C compared to electrical heating & A/C	Energy Consumption	-34	+95	-70
	Cost to serve	+34/+19	-4	-75
	Total cost	+300/+260	+210/+150	+220/+170
Adding hot off-peak storage to solar heating & A/C	Energy Consumption	+21	+5	+53
	Cost to serve	-65	-33	-3
	Total cost	-8/-13	±0	+19

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* These values include solar water and space heating.

** Where two values are shown separated by a slash (/), the first value pertains to 1985, the second to 1995. Where only a single value is shown, the percentage changes for 1985 and 1995 are the same or differ only slightly.

Where no numerical value is given with the + or - signs, the changes are small.

3. The combination of solar space conditioning with utility load management through thermal storage is beneficial in many cases. The best method of accomplishing load management is through a separate storage device which is electrically charged during off-peak hours. Combining solar storage and off-peak storage in a single container is practical in highly stratified storage devices only, such as tall cylindrical water tanks or well-designed rock beds.

4. The air-to-air heat pump is the most economical of all space heating and cooling systems investigated. Although it was analyzed in one location only, this conclusion is believed to be valid throughout the country. A different conclusion may be reached if heating-only systems are compared. This was not done in the present study.

5. The addition of off-peak storage to an electric water heating system is justified when the cost differential between on-peak and off-peak electric energy is greater than approximately 0.5 ¢/kWh. It increases energy consumption by less than 10% but significantly reduces the utility cost-to-serve. On the other hand, the homeowner must install a larger water heater.

6. Adding off-peak (electrical) storage to a solar water heater decreases utility cost and decreases total cost. The addition of off-peak storage in a separate tank requires a significant cost increase, but the utility's cost to serve is also reduced considerably. Although this analysis was performed for a single utility only, cost and performance comparisons show that this conclusion may be generally valid.

7. The addition of off-peak storage to an electric resistance space heating system increases total energy consumption on the order of 10% to 20%, it may cut the utility cost to serve by as much as one-half, but it does not result in an overall cost saving at all locations investigated. At the most favorable location (Daytona Beach) this system is less costly, at San Diego it is more costly until shortly after 1995 when it begins to break even, and at Philadelphia it has no effect on total costs.

8. The cost comparison between electric heating and solar heating backed up by electric resistance heating is extremely climate dependent and depends less on utility costs. At no location is solar heating cost competitive with conventional heating, nor will it become so through the end of the century, unless electric energy costs change drastically.

9. Solar heating systems save 50% to 80% of electrical energy depending on design. The cost to serve such solar systems is less than the cost to serve conventional resistance heating systems at all locations studied. However, the high capital cost of the solar systems makes their total cost higher than that of electric resistance systems.

10. The addition of off-peak storage to a solar space heating system increases energy consumption between 9% and 27% at the locations studied. The increase is higher at less favorable solar locations. The cost to serve those systems is reduced everywhere when off-peak storage is added. However, the overall costs show an increase at one location, a decrease at another, and no change at a third. The advisability of adding off-peak storage to solar heating systems must, therefore, be investigated in each individual case, taking proper account of climate and utility costs.

11. Solar assisted heat pumps have lower back-up energy consumption and lower costs to serve but higher total costs than solar space heating systems with electric resistance back-up.

12. The addition of off-peak storage to solar assisted or conventional heat pumps does not result in an overall cost reduction.

13. Solar heating combined with solar absorption air conditioning is not competitive with conventional electric heating and air conditioning anywhere in the country. While energy savings are achieved, utility costs are higher everywhere, even for the winter peaking utility studied. Total costs for solar heating/cooling systems are approximately 3 to 4 times the costs of conventional systems

in 1985, and 2.5 to 3.5 times conventional costs in 1995. Unless a different method of solar air conditioning can be developed, solar air conditioning with electric back-up is not likely to become commercial in this century.

14. The addition of off-peak storage to solar heating/cooling systems increases energy consumption by 20% to 35%, and decreases the cost to serve considerably. Overall costs are decreased in unfavorable solar climates (8 % to 13% in Philadelphia) and are increased in favorable climates (19% in San Diego).

15. Hot storage in solar air conditioning systems is somewhat more favorable than cold storage.

16. The presence of a solar heating system on an electric utility network decreases its fuel cost. Calculated on a *marginal* cost basis, this annual cost avoidance amounts to $550 per solar heating customer in Philadelphia for Philadelphia Electric Company in 1985, and it increases with time. Under present tariffs, this cost avoidance is beneficial to *all* customers of that utility, because it results in a decrease in their fuel charges of less than 0.01 ¢/kWh. However, the benefits of this cost avoidance do not accrue to the homeowner who has made an investment in a solar system. This could provide a rationale for so-called subsidies of solar systems.

1.9 RECOMMENDATIONS

1. Investigate the accuracy of temperature predictions for the following day based on the previous evening's weather forecast. The potential savings that can be obtained from off-peak storage depend to a large degree on good weather predictions. No comprehensive data on the accuracy of those predictions appear to exist.

2. Investigate whether the use of gas as a back-up energy source could be more advantageous than the use of electric energy investigated in this report.

3. Continue the development of other than solar absorption air conditioning systems that have a promise of lower first cost.

4. Perform an investigation to determine the interface between passive solar heated and cooled buildings and electric utilities.

5. Determine the electric tariffs that will be required to induce homeowners to install solar and off-peak storage systems in a manner that is advantageous to both the homeowner and the electric utility.

6. Continue the investigations into methods of marginal cost pricing for solar heating customers of electric utilities.

7. Determine what subsidies or introductory tariffs electric utilities could offer to homeowners willing to install solar and/or off-peak storage systems.

2. INTRODUCTION

2.1 BACKGROUND

With the increasing shortage of fossil fuels, it appears likely that, in the not-too-distant future, the preferred method of providing back-up energy to solar space and water heating systems will be electrical energy. This trend is apparent, although, at the present time, the majority of solar heating systems employ fossil fuel back-up energy. According to experts in the residential market, there exists severe consumer resistance to fuel oil as the energy source in new homes, because the prospective homeowner does not wish to be at the mercy of a foreign cartel that could shut off his energy supply at will; new connections for natural gas are no longer available in many growth areas of the country. This leaves electricity as the choice for back-up energy - in spite of the "horror" stories about excessively high electric heating bills that have been published in the daily press during the last few years. Most homeowners are confident that their solar system will supply the major portion of their heating energy and, therefore, they feel protected from these excessive bills.

Previous work performed at the Franklin Research Center (Ref. 2-1) showed that peak loads from solar heated homes at the time of the utility system peak are virtually identical to the loads from conventional electric resistance heating homes. Therefore, solar heating customers have lower load factors than conventional electric resistance customers because their total energy use during the year is lower. The load factor is the ratio of average load to peak load. It is the single most important characteristic pertaining to electric utility customers. A high load factor denotes a "desirable" customer, i.e., one with a relatively low cost to serve; a low load factor denotes the opposite. Solar heating customers, therefore, appeared to be less desirable customers than conventional electric heating customers.

In the case of a Pennsylvania winter peaking utility, peak loads from solar heated homes with electric resistance back-up at the time of the utility system peak averaged well over 95% of the loads from conventional electric resistance heated homes (Ref. 2-1). Other studies (Refs. 2-2, 2-3) yielded lower values for winter peaking utilities in different regions of the country. Work was performed on an evaluation of the coincidence between sunny days and cold days at different locations (Ref. 2-4). However, it constitutes a limited approach to the problem because, as a rule, winter peaking utilities experience their system peaks on cold days, but not necessarily on the coldest day of the year. Thus, such correlations may be indicative of the problem in a general way, but they do not predict how individual utilities will be affected by the addition of large numbers of solar heating customers to their systems.

Solar cooling installations, on the whole, are likely to be beneficial to electric utilities load patterns. In general, there exists a correlation between sunny weather and periods of summer peaking utility peaks which, of course, would be alleviated by solar cooling systems.

All of the above conclusions are valid only for solar systems that are operated in the conventional way: whenever the sun shines, the solar system satisfies the building instantaneous demand. When excess solar energy is available is it put in storage. Whenever the building demand exceeds the solar system's instantaneous capacity, stored energy is used to satisfy it. Auxiliary energy is used only when neither the collector nor the storage systems can provide sufficient energy to satisfy the building demand. For a solar heating system this operating logic results in minimizing the amount of auxiliary energy used during the year, i.e., it minimizes the building owner's perceived cost if he is on a straight energy rate - which is the case in the large majority of today's building owners. Reference (2-5) showed that, for a solar cooling system, this operating strategy does not even result in minimum auxiliary energy use for a solar cooling system, and more sophisticated operating modes must be followed. In reality (Refs. 2-1, 2-2, 2-6) minimizing auxiliary energy consumption is not a condition of long-run cost minimization to the consumer because, over the long run, electric rates will be adjusted to reflect costs, and significant cost increases will be incurred by the electric utilities due to the reduced load factors caused by that method of operating back-up heating systems. It would be to the advantage of both the homeowner and the utilities to operate solar heating systems in a mode that utilizes the inherent capability of their storage devices to reduce peak electrical loads from back-up heating.

2.2 UTILITY COSTS

It has been shown that minimizing auxiliary energy use does not guarantee minimum cost to the user over the long run (Refs. 2-1, 2-2, 2-6). Once a sufficient number of solar heating customers has been connected to a utility network, a utility will insist on deriving a revenue equal to its cost to serve these customers. If existing rates (which are based on the assumption that an electric heating customer obtains all of his space and/or water heat from electrical energy) produce a consistent revenue shortfall as indicated by Refs. 2-1 and 2-2, utilities will apply for rate relief. This occurred in Colorado in 1976 where a utility introduced a standby rate that would levy a monthly charge of $40 for certain customers that use auxiliary electrical energy on a standby basis only, if they used any electrical energy during the month. Solar heating customers would have been among these customers (Ref. 2-7). The financial penalty was considered to be so heavy that the proposed rate would have virtually stopped the spread of solar heating in the state. Intense pressure on the state Public Utility Commission resulted in an order to the utility to hold the rate in abeyance until additional testimony on the effects of the proposed rate had been taken. Although many utility economists consider that proposed rate excessive, it was proposed in response to the fact that solar heating customers have low load factors and are, therefore, expensive to serve* by an electric utility as long as they continue to operate their solar systems according to the "auxiliary energy minimization" strategy. Since electric utilities face a significant increase in the cost to serve these customers, rates for solar heating

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*On a per kWh basis.

customers will increase (unless other customers are asked to make up the revenue shortfall caused by the solar heating customers which becomes the less likely, the greater the penetration of solar heating in the utility service area) as long as solar systems are operated to minimize total auxiliary energy consumption. It would be highly beneficial to both utilities and homeowners to adopt operating strategies that take advantage of the inherent capability of storage devices to reduce utility peaks during system peak persiods even though the total amount of electrical back-up energy consumed may be increased. This would reduce the cost to provide service on the part of the utility and would permit cost reductions to solar customers.

2.3 Effect of Thermal Storage Size

One might initially believe that the utility peak load problem could be alleviated by increasing the storage size of solar heating systems. This would reduce the probability of the solar energy system requiring electric resistance backup during utility peak periods. In order to explore this possibility, the electrical energy demands of a home equipped with different heating systems were simulated during the actual hour of the utility system peak (Ref. 2-1). The heating systems were baseboard resistance heating, a solar assisted heat pump, and direct solar heating systems with electric resistance back-up and different size storage systems.

Table 2-1 shows a comparison of the electric energy demands during the hour of the local utility system peak for five consecutive winters. The solar heated house has a storage system of 2 gallons of water for each square foot of collector area. Except for the year 1972, there is no appreciable difference between the two systems as viewed by the electric utility. In that year, the solar heated house had a 21-percent lower electrical demand than the all-electric house because the day of the system peak occurred at the end of a short cold spell which had been preceded by five days with average temperatures 13°F above normal. This appears to be an unusual weather pattern because, in all other years, the

Table 2-1. Electric Energy Demands of a Single-Family Home During the Hour of Electric Utility System Peak, Allentown, PA. (from Reference 2-1)

Year	All-Electric House With Baseboard Resistance Heat (kW)	Direct Solar Heated House (kW)	Effect of Solar Heating on House Demand (%)
1975	9.6	10.0	+4*
1974	8.0	7.5	-6
1973	9.1	9.4	+3*
1972	7.8	6.2	-21
1971	8.8	8.6	-2

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*The increase in energy demand of the solar homes over that of the electric resistance heated home is due to duct and fan losses.

system peak occurred after a prolonged period of cold weather. Generation capacity of utility systems cannot be designed to meet unusually low peak loads which occur on the order of once in five years; rather, it must be capable of satisfying the high side of the probability curve of the load demand. Prudent design would therefore require that, as far as generation capacity is concerned, solar heated homes and all-electric homes are considered as contributing equally to the system peak of this winter peaking utility.

To determine the effect of increased storage size on the electrical demand of a solar heated house, the performance of the heating systems was simulated with the storage capacity tripled to 6 gallons per square foot of collector area. A comparison of the peak demands of the all-electric house and the solar heated house coincident with the utility system peaks for the years 1971 through 1975 is presented in Table 2-2. The oversized storage does, indeed, reduce the contribution of the solar heated home to the system peak. From a five-year average of 8.7 kW for the all-electric home, the contribution to system peak is reduced to 8.3 kW for the standard size storage and to 8.0 kW for the oversized storage. If the unusually warm winter (and low system peak) of 1972 is deleted from the comparison, the numbers are 8.9, 8.9, and 8.5, respectively. Thus, the increased storage results in a reduction to system peak contribution of 0.4 kW (4.5%).

This small decrease in coincident demand is obtained at a cost to the homeowner of close to $2000 assuming a conservative storage cost of 50¢/gal. A homeowner is not likely to make this investment in return for an expected annual energy saving of 4 to 5%, nor is a utility likely to offer sufficient inducement for him to do so. Thus, oversized thermal storage is not an efficient way of decreasing utility peak loads, and other methods of achieving this goal must be investigated.

Table 2-2. Electric Energy Demands of a Single-Family Home With Different Size Storage During the Hour of Pennsylvania Power & Light Company System Peak (from Reference 2-1)

Year	All-Electric House With Baseboard Resistance Heat (kW)	Solar Heat with 80 ℓ/m^2 Storage (kW)	Solar Heat with 240 ℓ/m^2 Storage (kW)	Change Due to Oversize Storage (kW)
1975	9.6	10.0*	9.7*	-0.3
1974	8.0	7.5	6.9	-0.6
1973	9.1	9.4*	9.0*	-0.4
1972	7.8	6.2	6.4	+0.2
1971	8.8	8.6	8.3	-0.3
Average	8.7	8.3	8.0	-0.3

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* The increase in energy demand of the solar homes over that of the electric resistance heated home is due to duct and fan losses.

2.4 PROJECT GOALS

Since the senior author of this report drew attention to the potentially deleterious effect of solar heated homes on electric utility load factors (Ref. 2-8), numerous investigations into this subject have been carried out. A good summary of these up to 1978 is given in Ref. 2-9, and later work is discussed in Ref. 2-10. More recent work has been published by the Solar Energy Research Institute (Refs. 2-11, 2-12). The Electric Power Research Institute has funded two series of studies (Refs. 2-13, 2-14) and is continuing to pursue this area (Refs. 2-15, 2-16).

Many studies of the solar/utility interface assume that current electric tariffs represent actual costs. In reality, the connection between tariffs and costs of service is not always direct; frequently, political considerations or considerations of social equity* enter into the setting of tariffs.

In order to steer clear of the tariff problem, the present study was planned to consider the homeowner/utility system as a whole, to concentrate on the costs incurred by this system as a unit, and to ignore the "internal" payments within this system: i.e., the payments between homeowner and utility. The external costs incurred by this system are the utility's cost to serve the homeowner, and the cost to the homeowner of installing (and maintaining) the equipment in his house. Payments of the homeowner to the utility are "internal", and are therefore ignored. The system which minimizes the costs incurred by this homeowner/utility system is the optimum system for society as a whole. It would be the task of future work to determine what inducements a utility or the Government would have to offer to a homeowner to induce him to install such an optimum system in his home.

Unfortunately, it was not possible to ascertain the true costs of service for all the utilities considered. In those cases, recently introduced off-peak and on-peak tariffs were used, after adjustments, as

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*For example, the concept of "life line rates" cannot be justified on economic grounds, but it is frequently justified as a measure of social justice.

surrogates for costs although the authors realize that the two are not identical. It is believed, however, that these tariffs are sufficiently representative of the true cost of service to justify the validity of the analysis. Where costs based on tariffs were used instead of actually established costs, this has been expressly stated in the appropriate sections of this report.

Electric utilities are under orders (Ref. 2-17) to determine the true costs of serving different customers at different times. These costs are becoming gradually available. Within a short time, therefore, it will be possible to use the methodologies established in this report to determine optimum solar and storage systems for all locations and utility service areas of the United States.

3. METHODOLOGY

3.1 Selection of Building and Heating/Cooling Systems

The objectives of this project were to develop and evaluate novel control strategies for solar heating/cooling systems that utilize electrical backup. These control strategies are designed to reduce electrical power demand during utility peak load periods.

A typical single-family suburban home expected to be built throughout the study period (1980-1990) was defined. The single-family dwelling was chosen because the market for such homes is well-defined and exists throughout the entire country. If desired, the energy performance and the effects on utilities of using the novel control strategies in multiple family dwellings can be evaluated in the future by the same methodology. The house is a conventional two-story dwelling with a floor area of 148 m^2 (1600 ft^2), insulated in accordance with best present practice for each location, and inhabited by a family of four. It is described in more detail in Appendix A.

Detailed energy consumption calculations were performed for this house equipped with conventional heating and cooling systems using hourly meteorological data for four locations in the United States. The results were checked against the utilities' historical experience and past energy consumption measurements. Where necessary, the analysis was modified to have the results agree with measured values.

A great number of solar space heating systems were then conceptualized.* Some of them incorporate offpeak energy storage to reduce peak electrical loads on the utility, and control logics for the efficient use of that storage were developed (see Section 3.2). The literature was extensively reviewed to include systems chosen by other investigators, particularly those under contract to DOE and EPRI (Ref. 3-1). In order to avoid unnecessary calculations required to identify the most suitable systems, several of the systems were discarded on the basis of qualitative or comparative evaluations. The remaining solar and conventional heating systems were then analyzed in either 15 or 7.5-minute intervals throughout

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*For detailed descriptions, see Appendix B.

the heating season by a Franklin Research Center modified version of the TRNSYS (Ref. 3-2) computer program and meteorological data.

Three types of domestic water heating systems that reduce utility peak loads were identified, one electric and two solar. A large number of these types of systems are in current use, and actual operating results are available. In addition, the performance of such systems was simulated for Daytona Beach and San Diego.

Several types of solar air conditioning systems using lithium-bromide absorption chillers were considered. These included systems with chilled water storage and systems with offpeak storage in the form of hot or chilled water. The solar air conditioning systems were assumed to have an auxiliary electric heating system to operate the absorption chillers when solar energy was not available. In practice, solar absorption systems nearly always use a fossil-fueled back-up system because the cost of fossil fuels is significantly less than that of electricity. However, from an electric utility's standpoint, if a solar air conditioning system has a fossil-fueled auxiliary system, it is as if the customer had no air conditioning at all since electricity is then only required for pumps and fans. In this study, one of the objectives was to determine the effect of electricity use by solar systems on electric utilities, consequently it was assumed that solar air conditioning systems would use electricity to meet auxiliary energy requirements.

Version 9.2 of the TRNSYS computer program was used in this study. Version 9.2 contains a simplified model of an ARKLA DUCS-2 lithium-bromide absorption chiller. A more versatile absorption chiller model was developed and used in the TRNSYS program to simulate the performance of solar cooling systems. Sensitivity studies were conducted to determine the effect of collector type, collector area and storage size on system performance. System simulations were performed for Philadelphia, Daytona Beach, San Diego and Columbus.

None of the heating/cooling systems were "optimized" in a strict analytical sense for the following reasons. Optimization depends on fuel cost which is different for each location and for each of the cooperating utilities. It also depends on the control strategy employed with each system. Thus, if each system were truly optimized, no two systems would have been alike, and comparisons between systems and between locations would have been difficult, if not impossible, to make. It was, therefore, decided to size the systems at each location for best performance based on the experience of solar installations that have actually been erected in those locations. While this does not result in a mathematical optimum, it results in systems which are close to that. Since the change in cost or energy performance of a solar system sized close to the optimum is small, the performance of the selected systems differs only slightly from the optimum. Furthermore, the purpose of the study was not to optimally size each system but to identify the system with the best residence/utility interaction. Therefore, as long as different systems are compared to each other in a consistent manner, the fact that each system is not strictly optimized does not materially affect the results.

3.2 CONTROLLERS

A considerable amount of work has been performed over the last few years on the subject of control of solar heating/cooling systems (Ref. 3-3). Most of them are concerned with the improvement of system performance through "optimal" control strategies. These "optimal" strategies are defined in different ways. Some of them are concerned with improving the analysis on which the control strategy is based (Refs. 3-4,3-5). Winn and his associates define three types of optimal controllers (Ref. 3-6). Controllers of the first kind minimize a measure related to the energy supplied to the space and the discomfort of its occupants. Controllers of the second kind maximize the difference between the useful energy collected and the pumping costs associated with the collection of solar energy. Controllers of the third kind combine collection and distribution functions. An optimal controller of the second kind has been installed in the Colorado State University House II. Compared to a conventional on-off controller, the optimal controller improved the solar coefficient of performance (defined as the difference between useful energy collected and pumping energy required, divided by the latter) of the CSU House by 6% on a clear day and by 16% on a cloudy day. However, the net energy gain (i.e., the difference between useful energy collected and pumping energy required) was negative on a sunny day and only + 0.3% on a cloudy day (Ref. 3-7). The suitability of the control function for this type of controller of the second kind is, therefore, not clearly proven.

Investigators at Rho Sigma also reported that proportional controllers do improve system performance on cloudy days but do not do so (or do so only slightly) on sunny days (Ref. 3-10).

A dramatic improvement in building energy performance was reportedly achieved through an adaptive control method (Ref. 3-8). However, the baseline control method of that particular building was seriously flawed and, therefore, the improvement shown is primarily due to a better control strategy and not due to adaptive control as such.

There is little question about the fact that proportional controllers can, indeed, improve the energy performance of solar systems. However, in many cases, this improvement may not be justified because of the significant increase in controller cost and complexity compared to a marginal increase in the solar energy collected (Ref. 3-9).

Since the purpose of the present project was not to optimize control system per se, but to optimize the interaction between solar systems and electric utilities, no effort was devoted to optimizing controllers as such; only on-off control modes were considered. If improved proportional or other controllers are developed and introduced in the marketplace, the results presented here will not be materially affected, since they are concerned with the macro effects on utilities and not with the micro effects of decreasing the energy consumption of a solar system by a few percent. The actual control strategies used for each of the conventional and solar systems investigated are given in Appendix B.

3.3 CONTROL STRATEGIES FOR OFF-PEAK STORAGE

The purpose of using off-peak storage is to prevent auxiliary or backup systems from operating during the electric utility peak period and thus contributing to the utility's system peak. To accomplish this, at the end of the off-peak period the storage must have been charged to meet the load not met by solar energy during the following on-peak period.

Four different strategies that can be employed in charging thermal energy storage during off-peak periods are listed in Table 3-1.

Method A - The simplest method is to charge the storage fully to its maximum level (or temperature) during every off-peak period.

Method B - The storage is charged off-peak to a level required to meet the maximum demand (design load) of the home for the entire peak period.

However the maximum demand or design load occurs only a small number of times over the course of the entire heating or cooling season. The load will be below the maximum or design level most of the time and both of the above mentioned strategies will overcharge storage most of the time. This overcharging of storage, to higher temperatures than required, leads to unnecessarily high heat loss from the storage tank. To avoid thermal storage overcharging and excessive heat loss, anticipatory charging strategies can be used.

Method C - At the beginning of the off-peak period a prediction of the expected average temperature during the following peak period is made. Using overall heat loss or heat gain coefficient of the house and the anticipated temperature, the expected heating or cooling load for the following peak period is predicted. The thermal energy storage is then charged during the off-peak period to a level required to meet the predicted heating or cooling load during the peak period.

Method D - Predictions of the solar radiation available and the expected average temperature for the following day are used to estimate the solar available to help meet the heating or cooling load during the following

Table 3-1. Control Methodology Summary

Method	Type	Behavior
A	Storage device fully recharged with backup energy during every off-peak period.	Causes high standby losses. With proper sizing, avoids all on-peak power demands.
B	Storage device recharged during off-peak period to a level required to satisfy maximum demand during subsequent on-peak period.	Slightly lower standby losses. Avoids on-peak demands.
C	Storage device recharged during the off-peak period to a level sufficient to satisfy demand during subsequent on-peak period based on expected temperatures during that period.	Smaller standby losses than for strategy (B). No on-peak demands.
D	Storage device recharged during off-peak period to a level sufficient to satisfy demand during subsequent on-peak period based on expected temperatures and solar collection during that period	Smallest standby losses. No on-peak demand.

peak period. The predicted solar contribution is then subtracted from the predicted heating or cooling load (based on the predicted temperature) to determine the amount of off-peak energy storage required to meet the heating or cooling load in the following peak period.

Both methods C and D require fairly accurate weather predictions and raise serious questions of responsibility for inaccurate predictions. For example, if the prediction overestimates the heating or cooling load or underestimates the solar contribution, the homeowner must pay for the excess energy charged into storage but not used, much of which will be unavailable for further use due to heat loss from the storage container. If, however, the prediction underestimates the heating or cooling load or overestimates the solar contribution, insufficient energy will be stored during the off-peak period and the heating systems will require utility power during the peak period, adding to the utility peak load.

Off-peak recharging of storage devices can lead to secondary utility peaks at the beginning of the off-peak period. This has already happened in West Germany in parts of which off-peak service is now available to every other customer only (Ref. 3-11). It is, however, relatively easy to enable the utility to manage off-peak loads in a manner that this does not occur. A simple set of load management strategies is indicated in Figure 3-1. It illustrates the differences in methods (B) and (C) of Table 3-1. It also shows that simple controls can be incorporated in the off-peak storage device which permit it to be charged either at the beginning of the charge period, or at the end of the charge period or, at a reduced rate, throughout the full duration of off-peak period. Given a neighborhood of a dozen or more houses, the figure shows how the judicious installation of control devices C_1, C_2 and C_3, each in one-third of the houses, will produce a fairly uniform utility load throughout the off-peak period. Controllers of this type can either be hard-wired into the storage system, or different charging rates can be actuated by utility-triggered devices. Such controllers, too, are considered to be state-of-the-art.

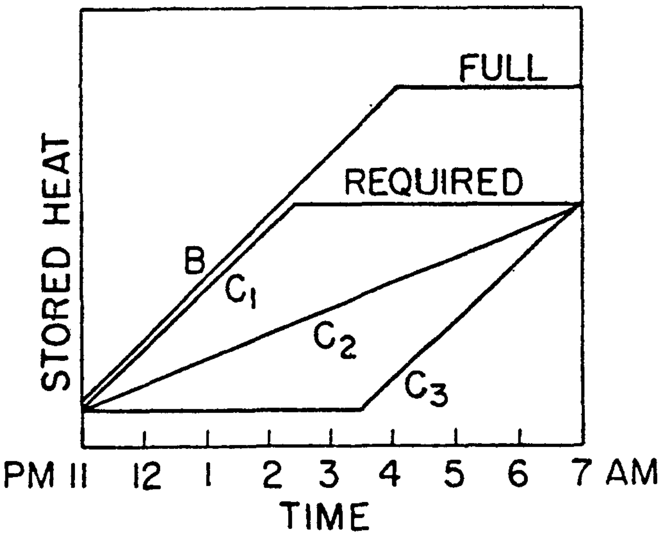

Figure 3-1. Strategies for Recharging Off-Peak Storage

3.4 EFFECT OF WEATHER PREDICTION

Method A is easy to implement. Method B requires a somewhat more sophisticated control because a certain amount of predictive capability is needed. This applies to strategies (C) and (D) to a much greater extent. It would be most efficient to have the electric utility supply the predictive data, because the data requirements exceed the capability available to the average homeowner. For example, the utility could send out a signal at the beginning of the off-peak period which would direct the storage device to be charged to the amount required. The technology to achieve this by either radio control or ripple control is available. On the other hand, a utility may hesitate to supply this service to customers because (in the winter) it would be charged with selling an unnecessary large amount of backup energy if the following day turned out to be warmer or sunnier than anticipated, and it would be blamed for insufficient heat if the opposite occurred (Ref. 3-11). The reverse would be true in the summer.

An alternate method of prediction could be provided by the U.S. Weather Service. The required information could be broadcast over radio and TV with the 10 pm or 11 pm news and weather report. For example, the announcer could say: "Turn your off-peak storage to number 16". This would make the control cheaper, but the homeowner would now be required to turn a dial to the indicated setting. If he is not at home during that time, he could obtain that information by dialing a telephone information number, say the local telephone weather forecast. This method would relieve the utility of the onus of making a wrong prediction, because people would blame the (government operated and therefore presumably impartial) U.S. Weather Service if the forecast turned out to be incorrect.

In order to determine the feasibility of using weather predictions made on the previous evening as an indication of the thermal storage requirements for the following day, attempts were made to determine the accuracy of the U.S. Weather Bureau and private forecasting services in predicting the weather, in particular the ambient temperature, twelve to fifteen hours in advance, (Refs. 3-12, 3-13), but none of the agencies had these statistics readily available. In view of the fact that utilities and other clients of private weather forecasting agencies are spending large amounts of money for these services, it was surprising to find that they had no quantifiable means of ascertaining the quality of these services. One utility offered us access to the temperature forecasts that they had received over the last few years together with tabulations of actual temperatures. This would have entailed a considerable amount of work because the records were in tabular, not in machine readable form. After further investigations we found out, however, that the forecasts were for the temperature in the center of a city and the measurements were taken at the airport of that city, a distance of several miles. Historically, the temperatures at the two locations have varied approximately five degrees; therefore, a comparison of the predicted and measured values was not likely to produce meaningful results, and this work was not undertaken. This experience points out, however, the need for an investigation into the accuracy of current weather prediction methods used in connection with thermal storage.

A simplified approach to weather forecasting was therefore examined which involved an investigation of the correlation between the dry bulb temperature at the start of the off-peak period, say 12 midnight, and the average ambient temperature during the following on-peak period. It was assumed that, if the average ambient temperature during the following on-peak period could be predicted, the heating load during that period could be estimated and the minimum required off-peak storage set temperature derived. This simple weather prediction procedure would be relatively easy to implement with an on-site control package.

Using Philadelphia weather data for the years 1964 and 1968, it was found that the midnight dry bulb temperature, on the average, correlates well with the average dry bulb temperature during the following day. However, there were a few days for which the correlations significantly overestimated the average dry bulb temperature during the following day.

Rather than search for a more reliable correlation, it was decided to use the 12 midnight dry bulb temperature minus 11°C (20°F) for estimating the load during the following on-peak period. This is a somewhat conservative approach, but it ensures that storage will be sufficiently charged for the worst case condition. The selection of an 11°C (20°F) temperature difference is based on an examination of the 1968 Philadelphia weather data. In 1964, only a 6°C temperature difference would have been required. If such a procedure were put into practice, it would be necessary to examine the weather data over several years for the specific location in order to determine the temperature difference necessary to insure that no auxiliary energy was ever required during an on-peak period.

The method used to determine the heating system storage temperature* for a specific off-peak period is outlined below. First, the load during the following on-peak period (Q_{op}) was determined by

$$Q_{op} = UA\ (T_{room} - (T_{12\ pm} - 11) \times (\text{no. of on-peak hours})) \qquad (3\text{-}1)$$

where UA is the building heat loss coefficient, T_{room} is the conditioned space thermostat setting, and $T_{12\ pm}$ is the ambient dry bulb temperature at the start of the off-peak period. The minimum usable storage temperature T_{min} has been chosen to be 35°C (95°F) based on practical considerations (i.e., comfort in the conditioned space and load heat exchanger size). On very cold days, however, heat from storage at or slightly above 35°C (95°F) will not be sufficient to meet the entire heating load due to the limiting rate at which heat can be transferred to the conditioned space through the load heat exchanger. Under these conditions, a higher minimum usable storage temperature (T_{mop}) at which stored

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*The storage "set" temperature is the temperature to which storage is heated during the off-peak period.

energy is just able to meet the load at the end of the on-peak period will be required. That is, on very cold days, the off-peak storage temperature at the end on the on-peak period must be greater than T_{mop} which will in turn be greater than 35°C (95°F). The temperature T_{mop} was found by

$$T_{mop} = T_{room} + \frac{[UA \times (T_{room} - (T_{12\ pm} - 11))]}{\varepsilon\ \dot{m}\ C_p} \qquad (3\text{-}2)$$

where ε is the effectiveness of the load heat exchanger, and $\dot{m}$ and C_p are the mass flow rate and specific heat of the load supply air, respectively. Then, the off-peak storage set temperature is determined by

$$T_{set} = T_{mop} + \frac{Q_{op}}{M\ C_p} \qquad (3\text{-}3)$$

where $M\ C_p$ is the thermal capacitance of the off-peak storage. The capacity of the heating element used to charge off-peak storage was chosen such that it was just capable of heating the storage to temperature T_{set} while at the same time supplying the load during the off-peak period under worst case conditions.

3.5 OFF-PEAK STORAGE SIZING

The procedures used to size off-peak storage for various types of heating systems are described below.

The off-peak storage sizing procedure used was derived from the procedure presented in (Ref. 3-14). The maximum quantity of energy that would be required from off-peak storage (Q_{reqd}) is

$$Q_{reqd} = UA\ (T_{room} - T_{design}) \times (\text{number of on-peak hours}) \qquad (3\text{-}4)$$

where UA is the building heat load coefficient, T_{room} is the desired room temperature, and T_{design} is the winter outdoor design temperature.

There is a minimum temperature (T_{min}) below which energy from off-peak storage cannot be used to meet the load. At the end of the on-peak period, the off-peak storage temperature should not be less than T_{min}. The temperature T_{min} can be found as follows:

$$T_{min} = \frac{Q_{reqd}}{\varepsilon\ \dot{m}\ (C_p)_a\ \text{(number of on-peak hours)}} + T_{room} \qquad (3\text{-}5)$$

where ε is the load heat exchanger effectiveness, $\dot{m}$ is the air mass flow rate, and $(C_p)_a$ is the specific heat of air. For liquid-to-air heat exchanger ε varies between 0.5 and 0.7. For rock or brick storage, $\varepsilon = 1.0$.

Depending on the type of system employed and/or on the storage medium used, there exists a maximum allowable storage temperature (T_{max}). For example, if water storage is used, a maximum temperature of 93.3°C (200°F) eliminates the need for a pressurized storage tank. If the system uses a water source heat pump, the maximum temperature equals 35°C (95°F) which is the maximum temperature usable by most water source heat pumps. Once Q_{reqd} and T_{min} are determined and T_{max} is chosen, the required off-peak thermal storage capacity $M\,(C_p)_s$ can be found as follows:

$$M(C_p)_s = \frac{Q_{reqd}}{T_{max} - T_{min}} \qquad (3\text{-}6)$$

where M is the storage mass, and $(C_p)_s$ is the specific heat of the storage material. Using this procedure, off-peak storage can be sized for the worst case condition (i.e. no solar availability on the coldest day).

The suggestion has been made that the storage system need not be sized to carry the house through the worst condition but that, on rare occasions, a decrease in occupant comfort could be tolerated for a short time. We do not believe that this procedure is to be recommended for a residence. People want their homes to be comfortable and, while they may tolerate a lack of comfort at their place of work for a limited period of time, they are not likely to do so in their own homes. This is borne out by the fact that the Federal Emergency Building Temperature Restrictions (EBTR) enacted during the 1979-1980 winter specifically exempted residences from the 65°F maximum heating and the 78°F minimum cooling temperature limitations. Electric utilities are well aware of the need to provide residential comfort. That is why in none of the off-peak storage experiments undertaken by that industry (Ref. 3-15) is the storage system undersized. Quite on the contrary: in the largest of these residential experiments (Ref. 3-16) the storage device is approximately 40% larger than would be theoretically required for the design day. In addition, the homeowner is provided with a "panic button" that he can actuate to obtain on-peak energy in case his storage is exhausted before the start of the off-peak period. The utility felt this was desirable to ensure full home comfort to the house occupants.

For all systems considered in this report, one of the ground rules was, therefore, that off-peak storage was sized sufficiently large to satisfy the building comfort requirements without ever resorting to on-peak power other than for auxiliaries, such as fans and pumps.

3.6 WEATHER DATA

Space heating requirements are directly related to the weather, which varies appreciably from year to year. It was necessary to select an actual year for which weather data would be modeled. If weather data averaged over several years are used, the averaging process removes extremes from the data, and it is these extremes which have a major effect on the performance of solar heating systems. The typical year was chosen after comparing monthly and annual heating degree days for the years 1963-1970 for Philadelphia with average monthly and annual values. Data for specific years were obtained from Climatological Data - National Summary, (Ref. 3-17), and average data were taken from the Climatic Atlas of the United States (Ref. 3-18). The year whose monthly and annual values were found to correspond most closely to the average was chosen at each of the four locations investigated.

A computer data tape containing hourly weather data, including the amount of solar radiation on a horizontal surface, was obtained for each location through the SOLMET (Ref. 3-19) program. These hour by hour data were used as input to the TRNSYS (Ref. 3-2) program to simulate operation of various space heating systems over the heating season.

Flat-plate solar collectors used for solar heating systems are generally mounted inclined with respect to the horizontal in order to increase the amount of solar radiation received. As a result, the radiation incident on the tilted collector surface must be calculated. The procedure for doing this from the insolation on a horizontal surface is contained in the TRNSYS computer program; it is based on the work of Liu and Jordan (Ref. 3-20).

3.7 ELECTRIC UTILITY INTERACTION

Out of the large number of solar heating systems analyzed, the six best performers were analyzed by the Philadelphia Electric Company (PECo), a subcontractor to the Franklin Research Center. Similarly, three air conditioning systems were analyzed. Assuming full penetration of solar systems into the electric home space conditioning market, PECo personnel calculated the diversity factors for these systems. The diversified loads were incorporated into the total utility load on a hourly basis throughout the year. Based on the planned generation mix for 1985 and 1995, annual costs-to-serve conventional and solar customers were determined using projected fuel costs and economic dispatch of all generating units.

In addition, the fuel savings on the part of PECo due to the use of solar and/or off-peak storage systems were determined. Details of these analyses are presented in Section 5.

Based on the results obtained by PECo, some of the systems were modified for use at other locations. Complete simulations of those systems were then performed for residences located in Daytona Beach FL, San Diego CA, and Columbus OH. Using data provided by utilities serving areas close to those locations (but not necessarily those particular cities*) the cost to serve buildings equipped with conventional and with solar heating/cooling systems with or without off-peak storage were then calculated.

These other cooperating utilities, Florida Power Corporation and San Diego Gas and Electric Company, were not actual subcontractors to the Franklin Research Center on this project. Therefore, the amount of work they could contribute was limited. Thus, the data obtained for these locations are not as exhaustive as those for Philadelphia. However, sufficient data were obtained to be able to draw certain conclucions with respect to the best systems and control strategies to be used.

Utility costs and consumer costs were added in order to determine the most desirable systems from the point of society. The former consist of capital investment for generation, transmission, distribution, metering (if required), and operating costs (mostly fuel); the latter consist of capital costs for system installation and any differences in repair and maintenance costs between conventional and new systems. This method has the advantage of not requiring any consideration of electric tariffs. Tariffs to induce desirable consumer actions and to reimburse utilities for their costs to serve these consumers should be the subject of a subsequent study.

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*For example, Daytona Beach is not actually served by the Florida Power Corporation, but its climate is quite representative of the climate in the service territory of that utility.

4. ENERGY PERFORMANCE OF RESIDENTIAL SYSTEMS IN PHILADELPHIA, PA

4.1 TYPICAL HOME

The typical home chosen for this study is a well insulated 148 m^2 (1600 ft^2) four bedroom home located in the Philadelphia suburbs. This home is representative of the homes now being built or planned to be built in the PECo service territory within the next five years.

The house is insulated with 22 cm (9 inches) of fiberglass in the ceiling, 9 cm (3.5 inches) of fiberglass plus 2.5 cm (1 inch) of styrofoam in the walls and has double paned windows. Overall heat loss coefficient of the house is 1035 kJ/hr °C (543.9 Btu/hr °F). Complete details of the construction and energy consumption of this house are given in Appendix A.

BASIC DATA

Weather Data

Space heating requirements are directly related to the weather which varies appreciably from year to year. The basic analysis was performed for a home in the Philadelphia suburban area. Weather data recorded at the Philadelphia International Airport are representative of the weather experienced in the Philadelphia suburbs where the majority of new construction is taking place.

The typical year was chosen after comparing monthly and annual heating degree days for the years 1963-1970 for Philadelphia with average monthly and annual values. Data for specific years were obtained from Climatological Data - National Summary, (Ref. 4-1), and average data were taken from the Climatic Atlas of The United States (Ref. 4-2). The monthly and annual values for the year 1968 were found to correspond most closely to the average. In 1968, Philadelphia had 5078 heating degree days or 23 (.5%) less than the average 5101.

Heating and Cooling Seasons, Peak Loads

The space heating season in Philadelphia is defined by the local electric utility to last from October 1 through May 31. For this reason, the performance of various heating systems were simulated for January 1 - May 31 and October 1 - December 31 of the 1968 calendar year. Cooling systems were simulated for June 1 - September 30 of 1968.

For 1968 the peak heating load on the Philadelphia Electric Company occurred at 9 AM on January 9. This time was also identified by PECo as the maximum residential heating class peak demand for 1968. Included with the simulation results of each heating system is a plot of the electrical energy consumption of each system for January 9th and 10th. This plot gives an indication of the effect of each of the heating systems on the utility peak load.

The peak cooling load on the Philadelphia Electric Company for 1968 occurred at 2 PM on July 1.

4.2 ENERGY ANALYSIS OF SPACE HEATING SYSTEMS (For details see Appendix B)

4.2.1 Conventional Resistance Heating - Base System

The base system for this study is an electrical resistance duct heater. Conversion and transfer of the electrical energy to thermal energy in the resistance coil and to the air stream is assumed to be 100% efficient. Therefore, the electrical energy consumption of this system is equal to the heating load of the house. The annual energy consumption of this system is 64.3 GJ (17,800 kWh). Figure 4.1 shows the hourly electrical energy consumption of this system during the utility winter peak day and the following day.

4.2.2 Resistance Heating with Off-Peak Storage

A 2.8 m_3 (744 gal) insulated water tank with a 130,000 kJ/hr (123,000 Btu/hr) resistance heating coil is used to provide off-peak energy storage. During the off-peak period the tank is heated to set temperatures based on the 12 pm temperature as described in Section 3.

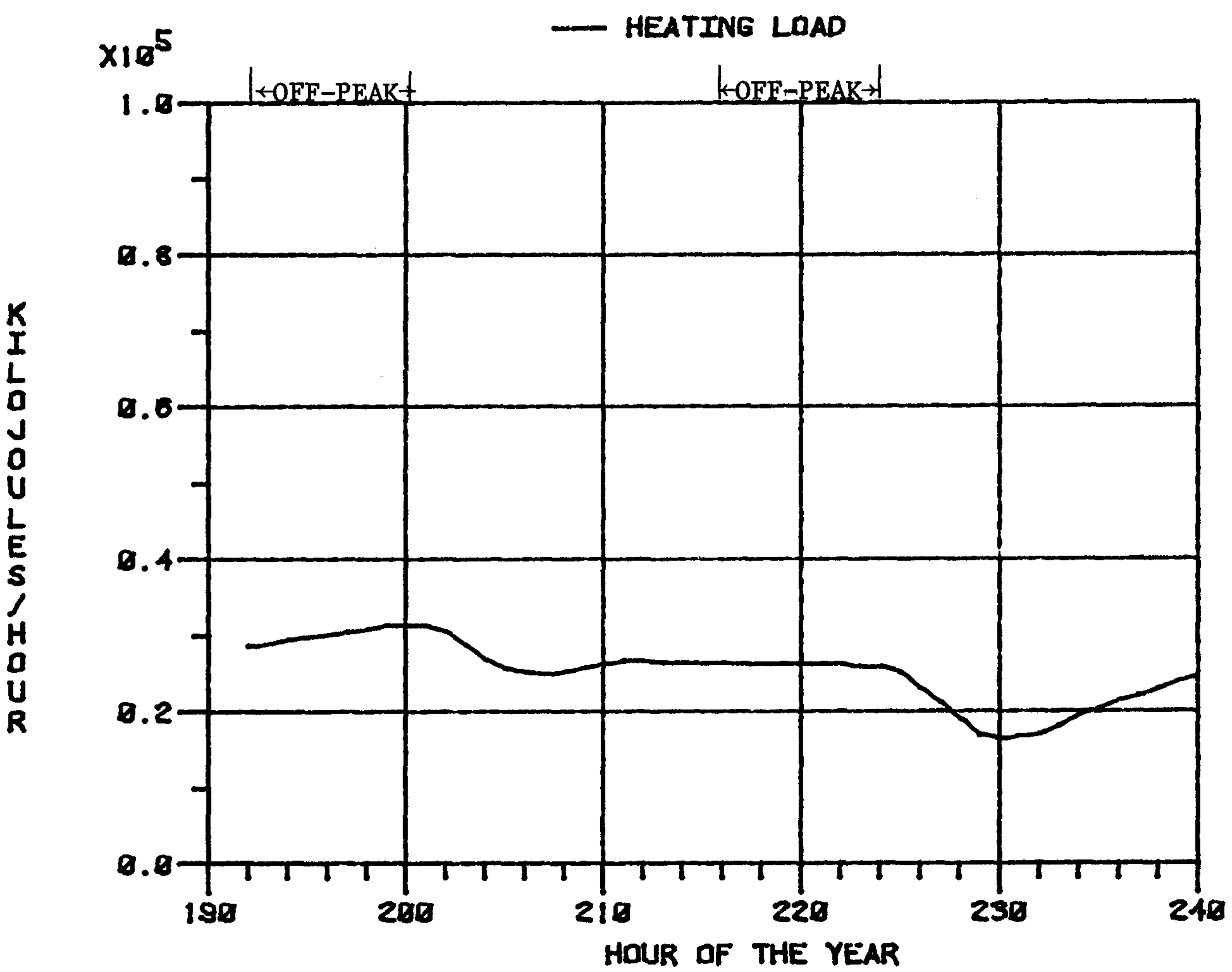

Figure 4-1. Electrical Energy Consumption of the Resistance Heating System During the Peak Heating Load Period (Electrical Consumption = Heating Load)

With insulation the heat loss coefficient of the tank is 1.5 kJ/hr m^2°C (0.073 Btu/hr ft^2°F or R - 13.6).

During the peak period, the hot water from the tank is circulated through a heat exchange coil in the air duct where it heats the air being delivered to the load. Figure 4.2 shows a schematic representation of this system.

Simulation Results

The yearly energy consumption of this system is 74 GJ (20,500 kWh), an increase of 10 GJ (2700 kWh) over the yearly energy consumption of the conventional resistance heating system. This 14% increase is due to (1) stand-by heat loss from the off-peak storage tank and (2) energy required to pump the stored hot water through the coil.

Figure 4-3 shows the energy consumption of this heating system for the PECo residential heating peak during 1968. As seen in the figure the energy consumption during the peak period is virtually eliminated (0.12 kW on peak power is required) with almost all the energy consumption occurring during the off-peak period.

4.2.3 Conventional Solar System

The major components of this system are shown schematically in Figure 4-4. The components used in this model are chosen to represent the most commonly used components in solar space heating systems today. Forty-two square meters (450 ft^2) of flat plate solar collectors with two glass covers and a flat black absorber coating are used in this model. The collectors face due south and are tilted at an angle of 50° (latitude + 10°) from the horizontal. Water from an insulated storage tank is circulated through the collectors by a pump controlled by a differential thermostat. Thermal energy storage (TES) is provided by a 3.4 m^3 (900 gal) insulated water storage tank. Hot water from the storage tank is circulated through a coil located in the air duct of the house to meet the heating load. An electrical resistance coil, located

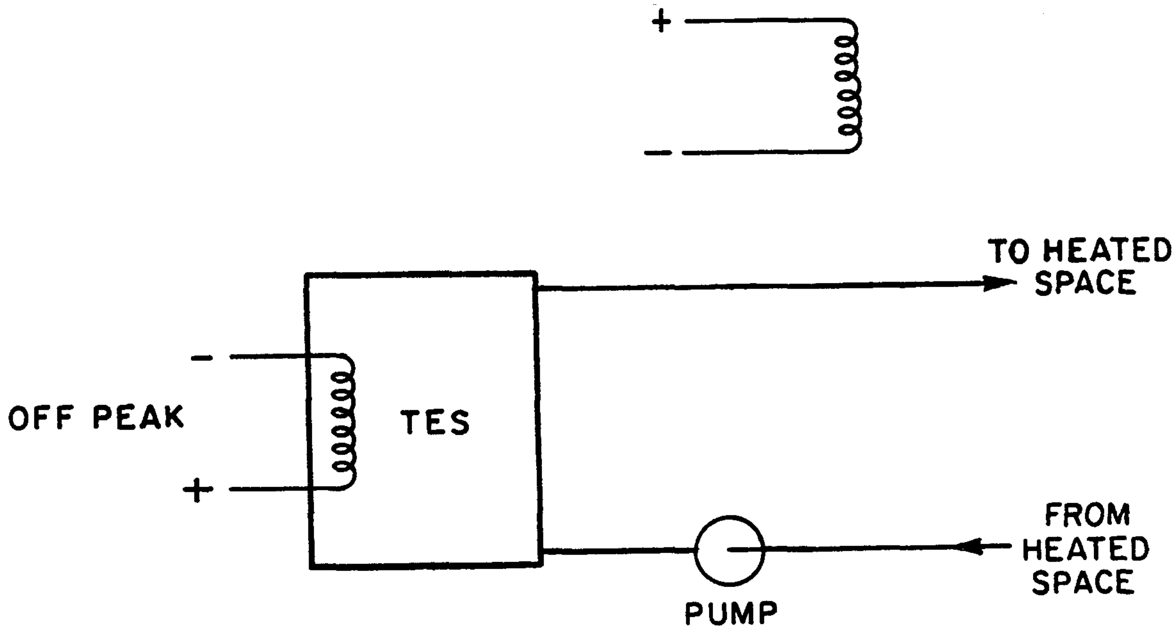

Figure 4-2. Resistance Space Heating with Off-Peak Storage

downstream of the hot water coil, in the air duct, provides auxiliary energy to the house whenever the solar system cannot meet the heating load.

Simulation Results

Of the 64 GJ (60.9 x 10^6 Btu) space heating requirement of the house, 42 percent, is provided by the solar heating system. The remaining 36.8 GJ (35.4 x 10^6 Btu) is met by auxiliary electrical power. In addition, 1.8 GJ (500 kWh or 1.7 x 10^6 Btu) of electrical power is consumed in operating the two circulation pumps. The total electrical power consumption of this system is therefore 38.6 GJ (10,700 kWh).

During the residential heating peak of the electric utility, this solar system has the same electrical power demand (8.66 kW) as the base resistance heating system, as shown in Figure 4-5. This is due to the fact that the utility peak occurs on a cold day preceded by several cold

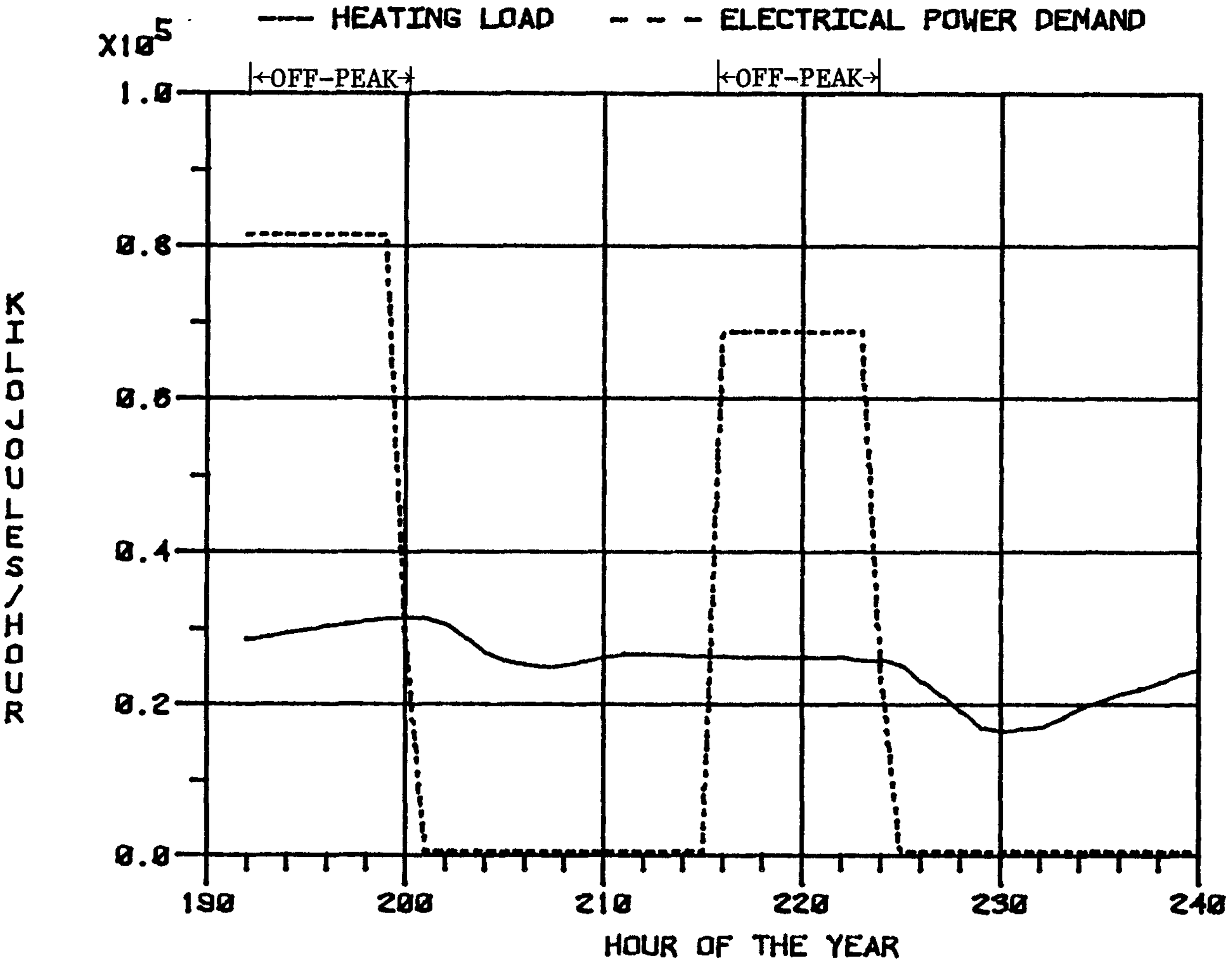

Figure 4-3. Electrical Energy Consumption of the Resistance Heating System with Off-Peak Storage During the Peak Heating Load Period.

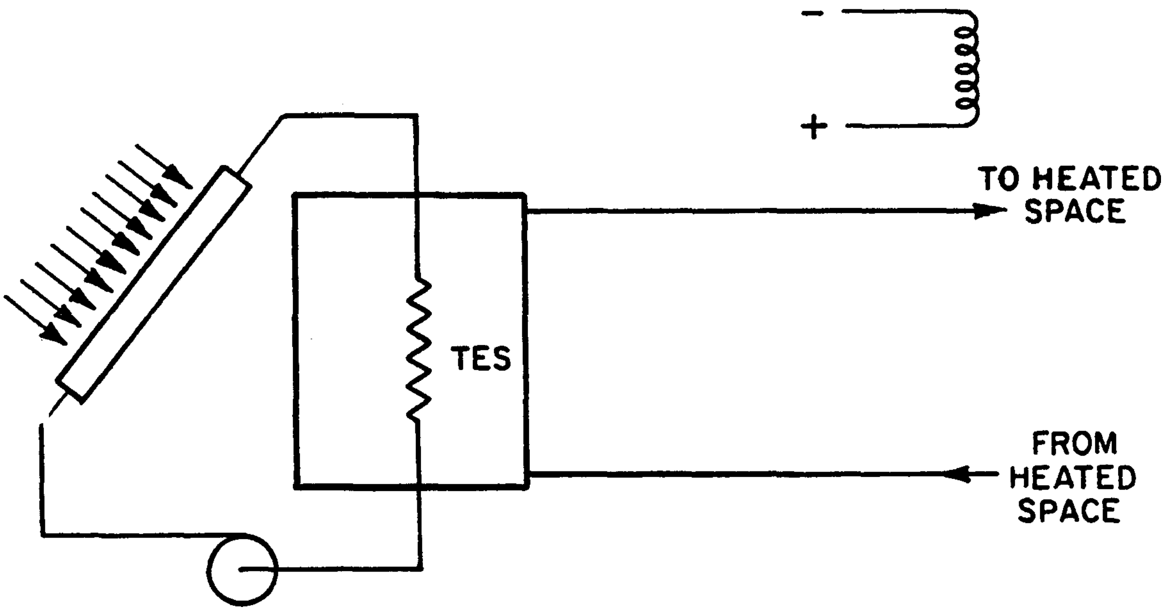

Figure 4-4. Conventional Solar Space Heating System

days with high heating demands. The low temperatures decrease the efficiency of the solar collectors while the high heating loads rapidly deplete the energy in storage, leaving an insufficient amount of stored energy to carry over until solar energy is again available for collection.

Performance results of the solar energy system are given in Table 4-1.

The collector efficiency determined by the simulation is 23%. This is due to use of the solar system for space heating only. During the fall and spring, where there is little or no heating load, the storage tank temperature remains high, thus reducing the efficiency of the solar collectors rather drastically.

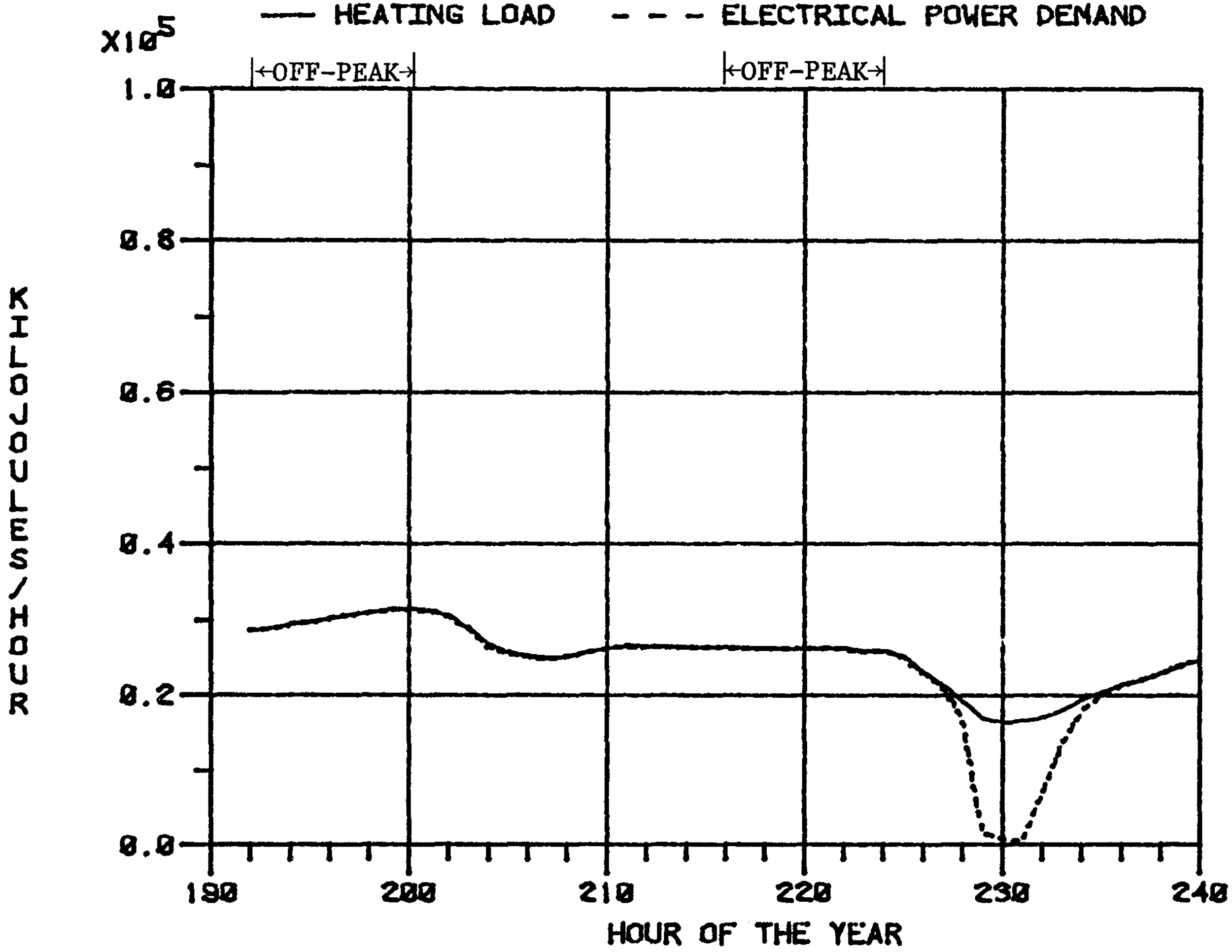

Figure 4-5. Electrical Energy Consumption of the Conventional Solar System During the Peak Heating Load Period

Table 4-1 Performance of Conventional Solar Heating System

	GJ	Btu
Solar Radiation Incident on Collectors	132	(125×10^6)
Solar Energy Collected and Delivered to Storage	31	(29×10^6)
System Efficiency - $\frac{\text{Energy Collected}}{\text{Incident Energy}}$	23%	
Energy Lost from Storage	4.8	(4.6×10^6)
Storage Efficiency - $\frac{\text{(Energy into Storage-Energy Lost from Storage)}}{\text{(Energy into Storage)}}$	84%	

4.2.4 Solar Heating System with Off-Peak Energy in the Solar Storage Tank

A resistance heating coil is placed in the water storage tank of the conventional solar system. During the off-peak period, the storage tank temperature is raised to a level required to meet the anticipated peak period heating load. The anticipated load is determined using the 12 midnight temperature as discussed in Section 3. A schematic representation of this system is shown in Figure 4-6.

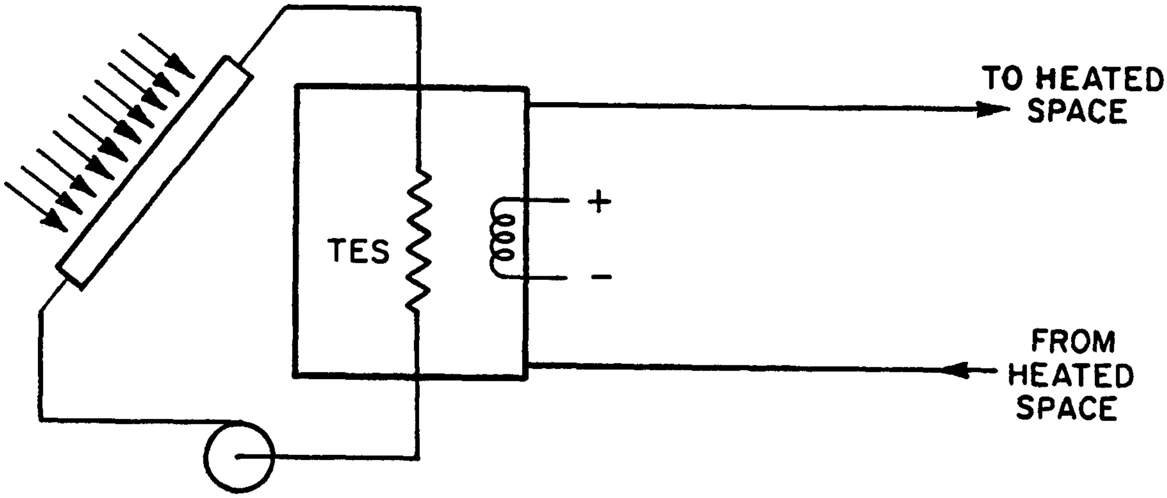

Figure 4-6. Solar Space Heating System with Off-Peak Energy in the Solar Storage Tank

This solar system is identical to the conventional solar system except for the addition of 36 kW (123,000 Btu/hr) resistance heating coil in the storage tank, and the removal of the duct mounted electrical heating coil.

Simulation Results

The annual electrical energy consumption of this system is 77 GJ (73×10^6 Btu). No useful energy is gained from the solar collector system. Because the solar storage tank is heated to a high temperature during every off-peak period, the solar collectors are never utilized since the storage temperature is above the collector temperature. Since the solar system contributes no energy to the heating load, this system operates essentially the same as the resistance heating system with off-peak storage. The slight increase in electrical energy consumption of this system, 77 GJ compared to 74 GJ for the off-peak resistance, is due to the increased surface area of the larger storage tank which increases the heat loss.

The profile of the electrical energy demand of this system during the peak load period is shown in Figure 4-7. This profile is identical to the profile for the resistance heating system with off-peak storage shown in Figure 4-3.

4.2.5 Solar Heating System with a Separate Off-Peak Storage Tank

In this system a second water storage tank is added to the conventional solar system for storage of off-peak energy. The second tank, hereafter referred to as the off-peak tank, is identical (2.818 m^3 and R-13.6 insulating value) to the tank used in the resistance heating with off-peak storage system discussed in Subsection 4.2.2. Charging of the off-peak tank is based on the 12 midnight temperature as discussed in Section 3. Components of the solar system (collectors, pumps, controller, and storage tank) are identical to those used in the conventional solar system described in Subsection 4.2.3. Figure 4-8 is a schematic representation of this heating system.

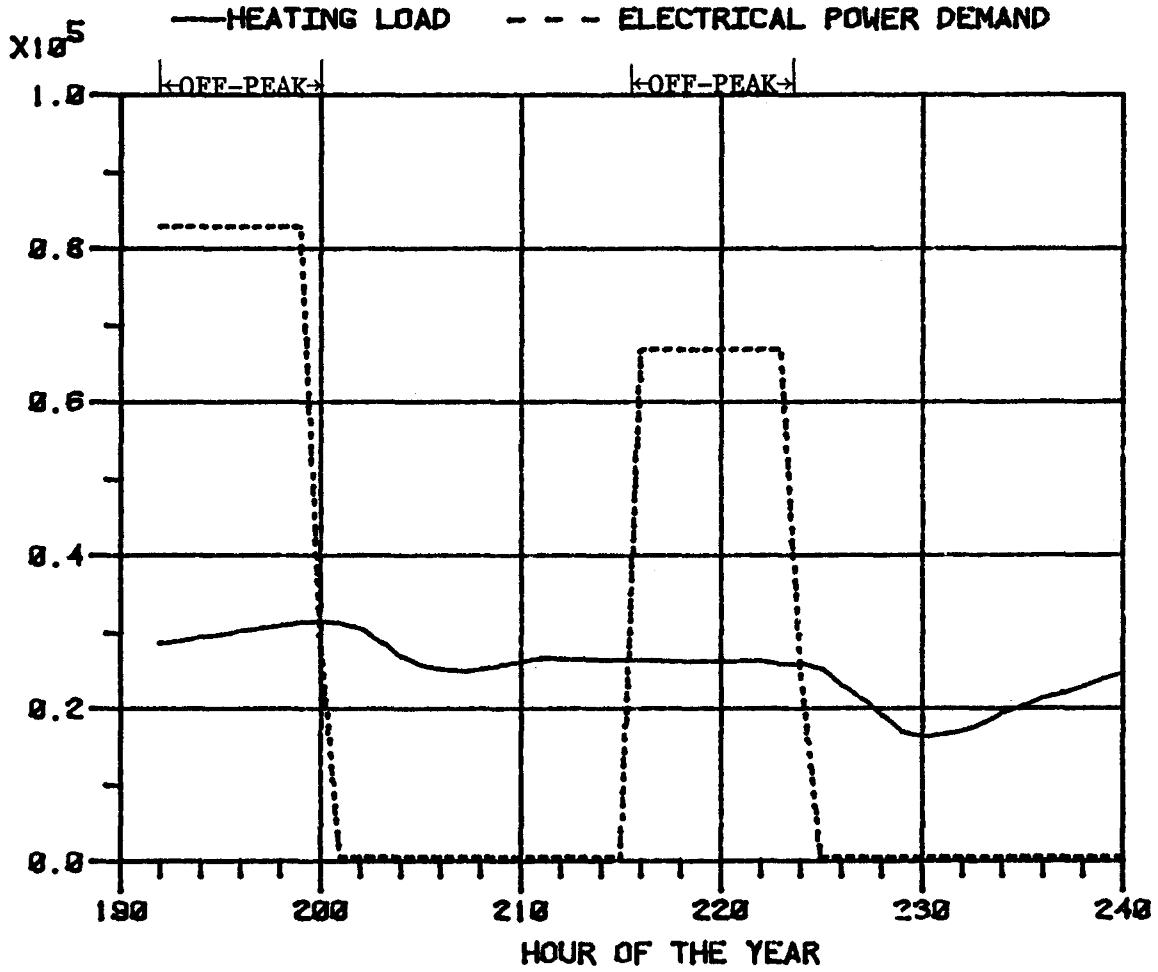

Figure 4.7. Electrical Energy Consumption of the Solar Heating System with Off-Peak Storage in the Solar Storage Tank During the Peak Heating Load Period

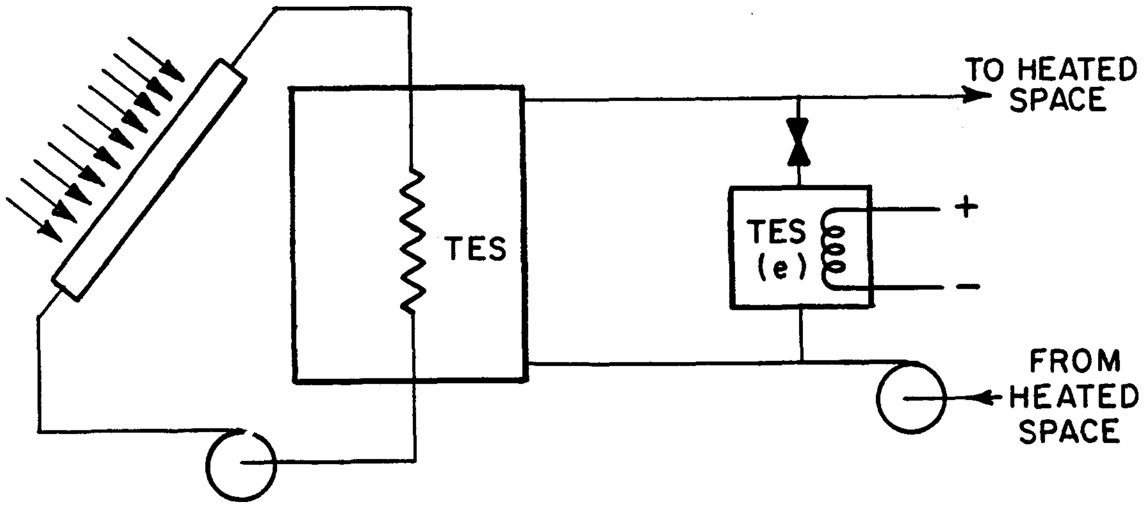

Figure 4-8. Solar Space Heating System with a Separate Off-Peak Storage Tank

When there is a heating requirement, a choice between using hot water from the solar storage tank or from the off-peak storage tank to meet the load has to be made. Whenever the solar storage tank temperature is above 35°C (95°F) water from this tank is circulated through the hot water coil. However, if the solar storage temperature is below 35°C or the solar storage cannot meet the entire heating load, water from the off-peak storage tank is circulated through the coil to meet the load. By giving first use priority to the solar storage tank, its temperature is kept at a minimum. This allows the collectors to operate at optimal efficiency and to contribute as much energy as possible to the total heating load.

Simulation Results

The total electrical energy consumption for this system is 47 GJ (12,900 kWh) for the simulation year. This is a 28% reduction from the base system (resistance heating) consumption of 65 GJ. Simulated performance results of the solar system and the off-peak storage are listed in Table 4-2.

A plot of the electrical energy demand of this system during the peak heating load is shown in Figure 4-9. As shown there, the electrical energy demand of this system is virtually eliminated (0.12 kW) during the peak load period.

Table 4-2. Performance Results of Solar Heating System with Separate Off-Peak Storage

	GJ		Btu
Solar System			
Incident Solar Radiation on Collectors	132		(125×10^6)
Energy Delivered from Collectors to Storage	31		(29×10^6)
Collector Efficiency		23%	
Heat Loss from Solar Storage	4.9		(4.6×10^6)
Solar Storage Efficiency		84%	
Off-Peak Storage Tank			
Auxiliary Energy Input into Storage	44		(41×10^6)
Heat Loss from Storage	5.9		(5.5×10^6)
Off-Peak Storage Efficiency		87%	

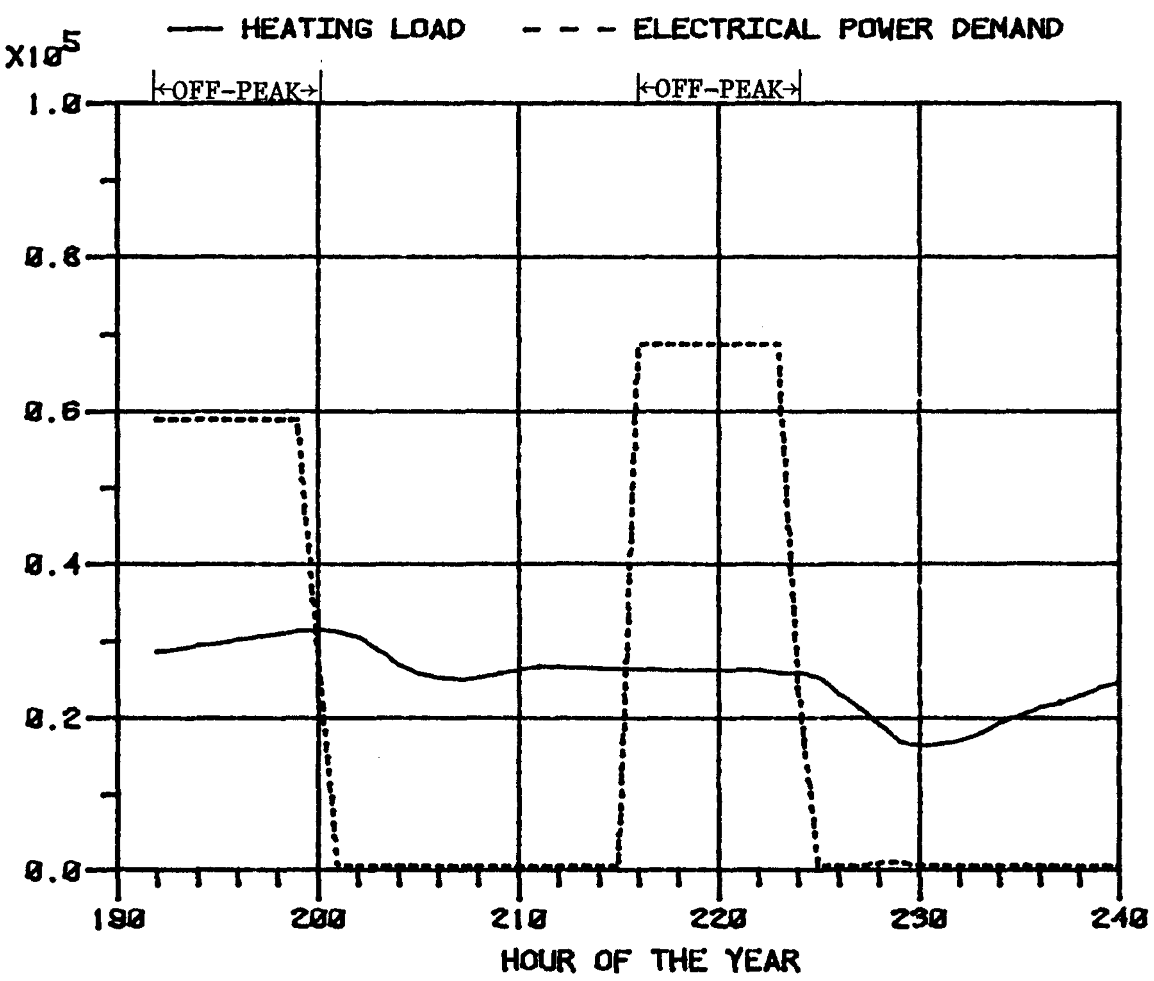

Figure 4-9. Electrical Energy Consumption of the Solar Heating System with Separate Off-Peak Storage Tank During the Peak Heating Load Period

4.2.6 Conventional Heat Pump

An outdoor evaporator coil extracts energy from the ambient air with an indoor condensing coil, located in the hot air duct, supplying energy to the heated space. For backup energy, a resistance heating coil is placed in the hot air duct downstream of the condensor coil to make up any portion of the heating load not met by the heat pump. Figure 4-10 shows a schematic representation of this system.

Simulation Results

The electrical energy consumption of the air to air heat pump is 27 GJ (7,500 kWh) for the simulated heating season. This is a 58% reduction from the base (electric resistance) heating system and represents a seasonal performance factor (SPF) of 2.3.

The peak electrical demand of this system is shown in Figure 4-11. As shown, the conventional heat pump reduces the peak load energy demand by 23% but still has a considerable power demand (6.7 kW) during the utility's peak period.

4.2.7 Heat Pump with Off-Peak Storage

Space heating is supplied by a dual source heat pump having both air source and water source evaporators, with an off-peak water storage tank supplying energy to the water source evaporator, in this system. Dual source heat pumps of this type are now becoming commercially available.

The water source evaporator is located in a 7.56 m^3 (2000 gallon) insulated water storage tank. The tank is insulated to a value of 1.5 kJ/mm^2°C (0.073 $Btu/hr/ft^2$°F or R - 13.6). During every off-peak period of the heating season, the water tank is heated to 35°C (95°F), the maximum operating temperature for the water source evaporator. A schematic representation of this system is shown in Figure 4-12.

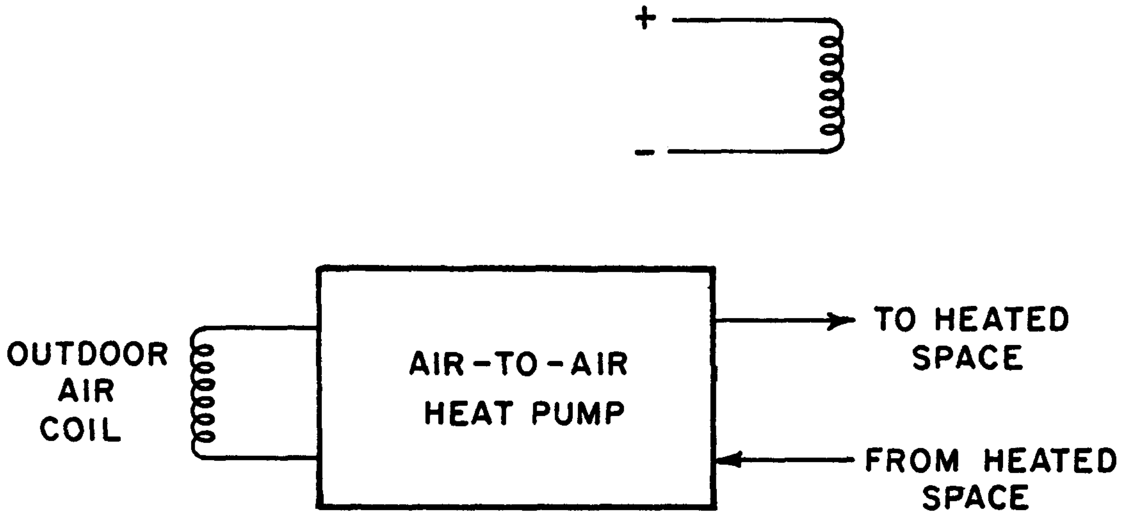

Figure 4-10. Conventional Air to Air Heat Pump System

To minimize electrical energy input to the water storage tank, the air source evaporator is operated preferentially to the water source evaporator. Only when the air source evaporator cannot meet the full heating load is the water source evaporator used to make up the difference.

Simulation Results

The electrical energy consumption of this system is 41 GJ (11,500 kWh) for the simulated year. This is a 11% increase compared to the conventional air to air heat pump and yields a SPF of 1.55. The peak load energy consumption of this system, (3.78 kW) as shown in Figure 4-13, is 43 percent of the base system energy consumption.

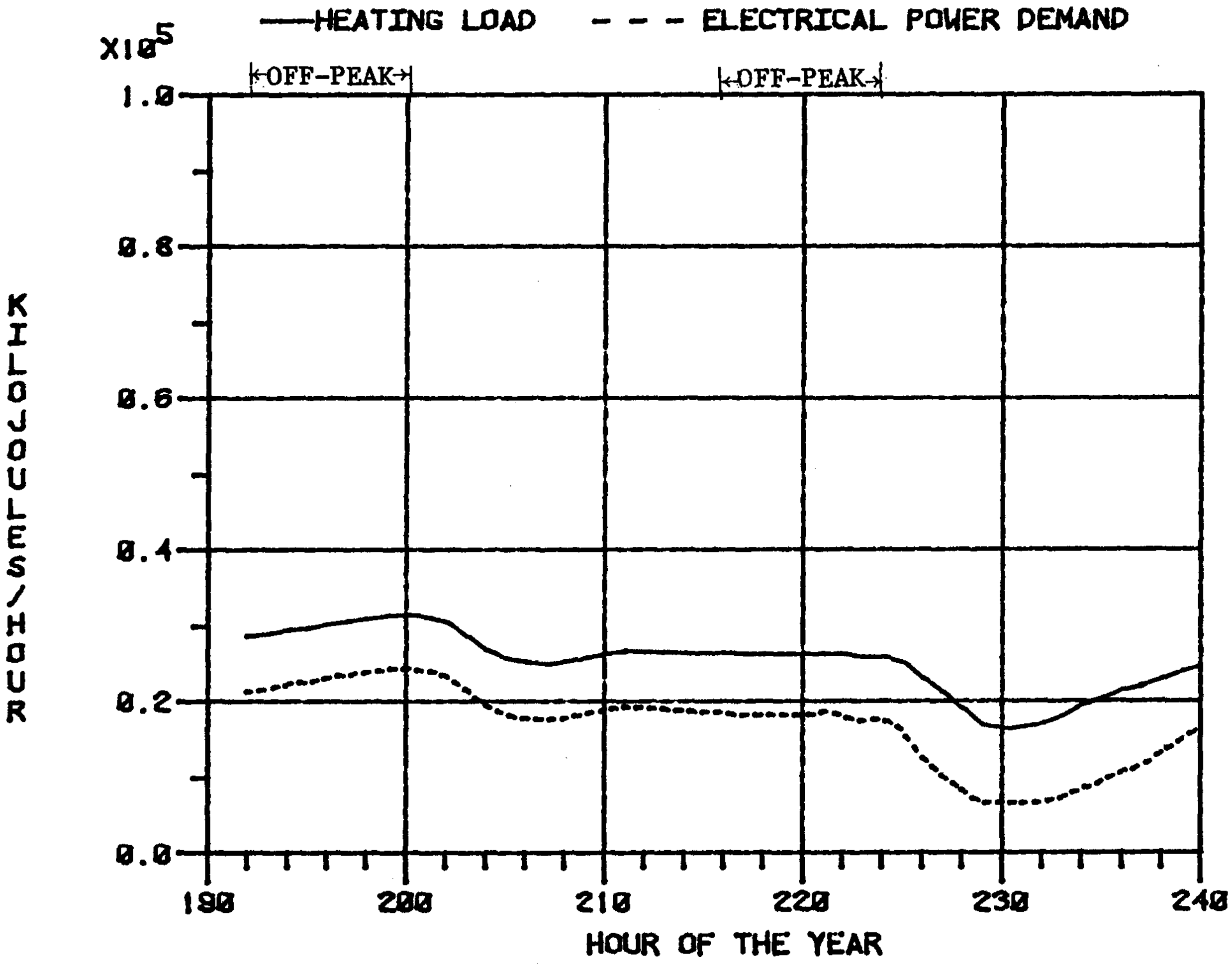

Figure 4-11. Electrical Energy Consumption of the Conventional Heat Pump During the Peak Heating Load Period

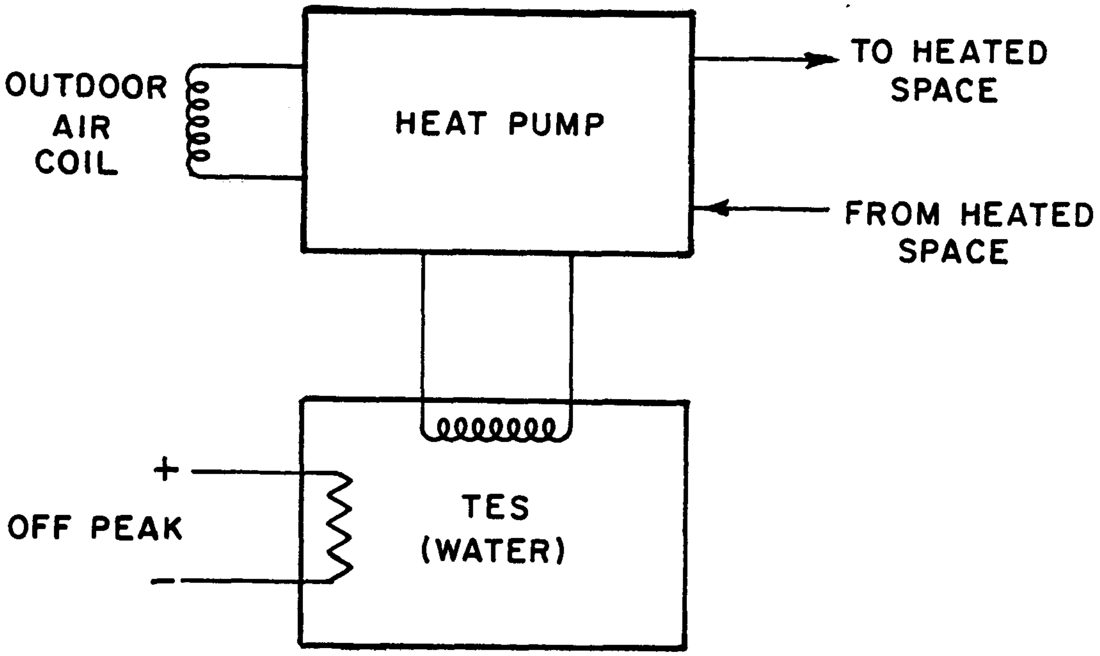

Figure 4-12. Heat Pump with Off-Peak Storage

Listed below in Table 4-3 is the performance of the water storage tank for the simulated year.

Table 4-3. Performance of Off-Peak Water Storage

	GJ	Btu
Energy Input to Storage Tank	18.7	(17.7×10^6)
Energy Loss from Storage Tank	5.1	(4.9×10^6)
Storage Efficiency	73%	

4.2.8 Solar Assisted Heat Pump

A solar energy system is used to provide energy to a water-to-air heat pump (in series between the solar system and the load), which provides the required energy to meet the heating load to the hot air duct.

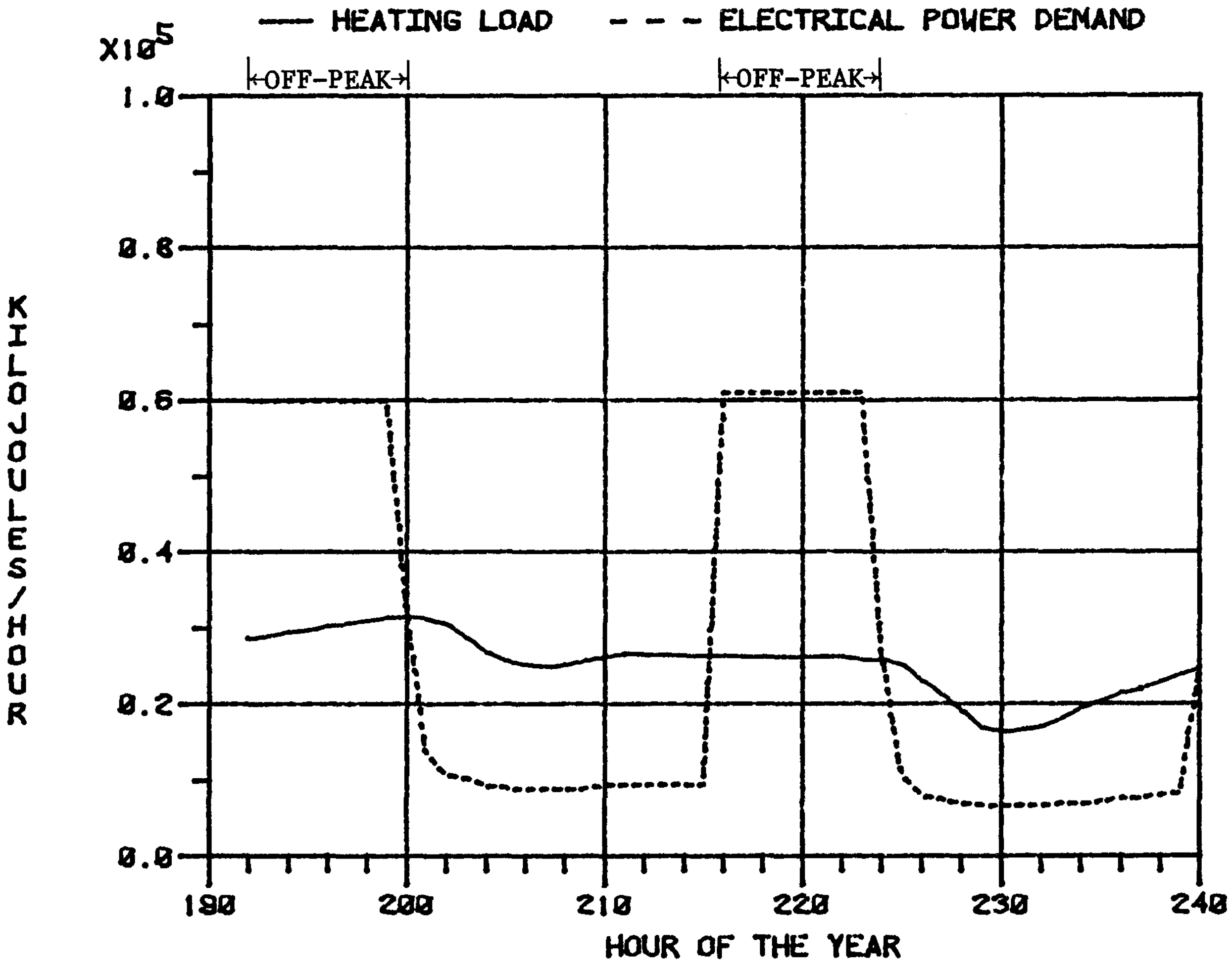

Figure 4-13. Electrical Energy Consumption of the Heat Pump with Off-Peak Storage System During the Peak Heating Load Period

Water from the storage tank of the solar system is circulated through the evaporator of the heat pump. A resistance heating coil, located downstream of the heat pump condensing coil, provides back-up energy should the heat pump be unable to meet the entire heating load. Figure 4-14 shows the configuration of this system.

Components of the solar energy system modeled here are identical to the components in the conventional solar system described in Subsection 4.2.3.

Simulation Results

The electrical energy consumption of this system is 33 GJ (9,000 kWh) for the simulated year. This results in a SPF of 1.94 for the system. As shown in Figure 4-15, the peak load of this system is equal to the heating load, thus offering no reduction in the demand of utility power at the peak load. This high peak demand is due to the unavailability of energy from the solar system during this very cold period.

The performance of the solar system for the simulated heating season is given in Table 4-4.

Table 4-4. Performance of Solar Components in Solar Assisted Heat Pump System

	GJ		Btu
Incident Solar Radiation on Collectors	132		(125 x 10^6)
Energy Delivered from Collectors to Storage	36		(33.8 x 10^6)
Collector Efficiency		27%	
Energy Loss from Storage	4.3		(4.1 x 10^6)
Storage Efficiency		88%	

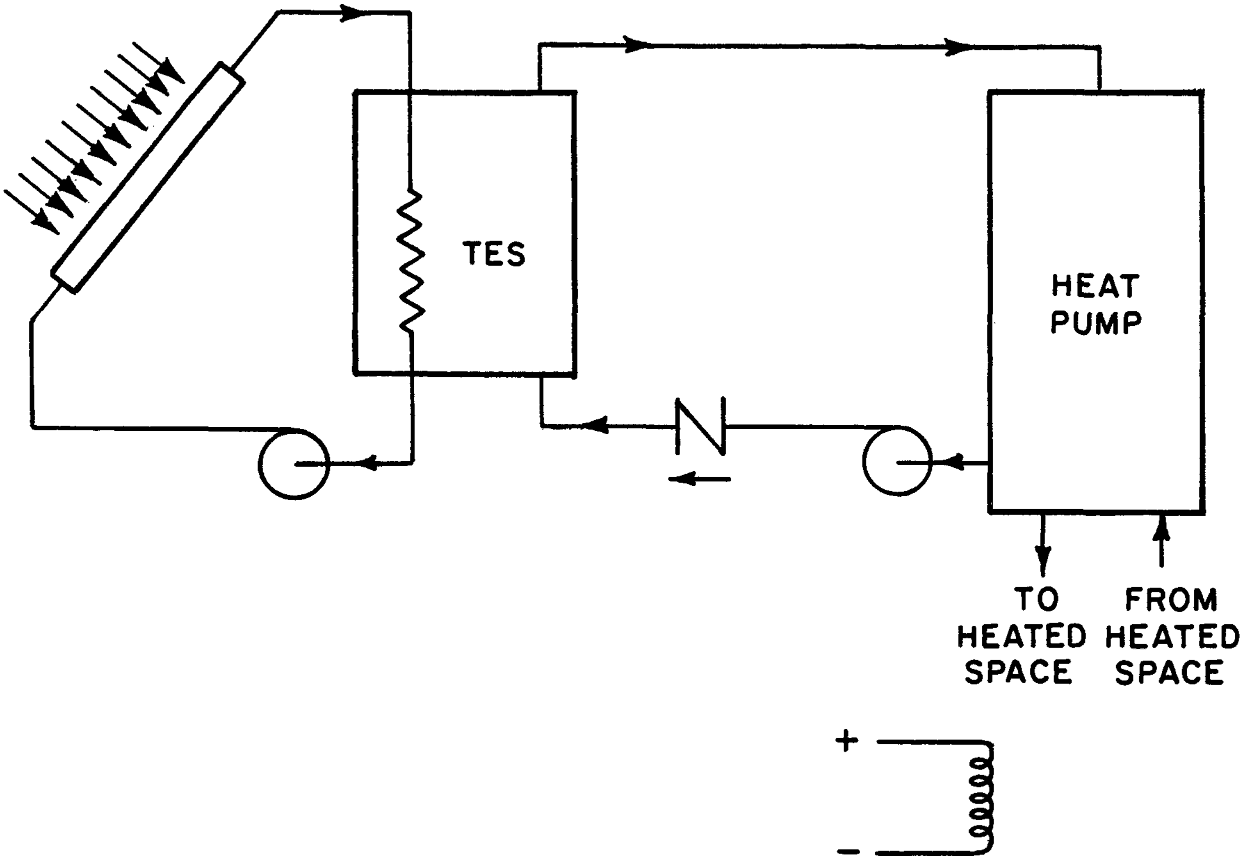

Figure 4-14. Solar Assisted Heat Pump

The increase in collector efficiency of this system, 27% compared to 23% for the Conventional Solar System, is due to the low minimum utilization temperature of the water source heat pump. In the conventional solar system, the thermal storage must be above 35°C (95°F) to provide energy to the load, while the water source heat pump can utilize energy from storage down to 13°C (55°F) in meeting the heating load. Therefore, when the storage temperature is between 13°C and 35°C, this system can utilize stored solar energy while the conventional solar system relies solely on backup electrical power.

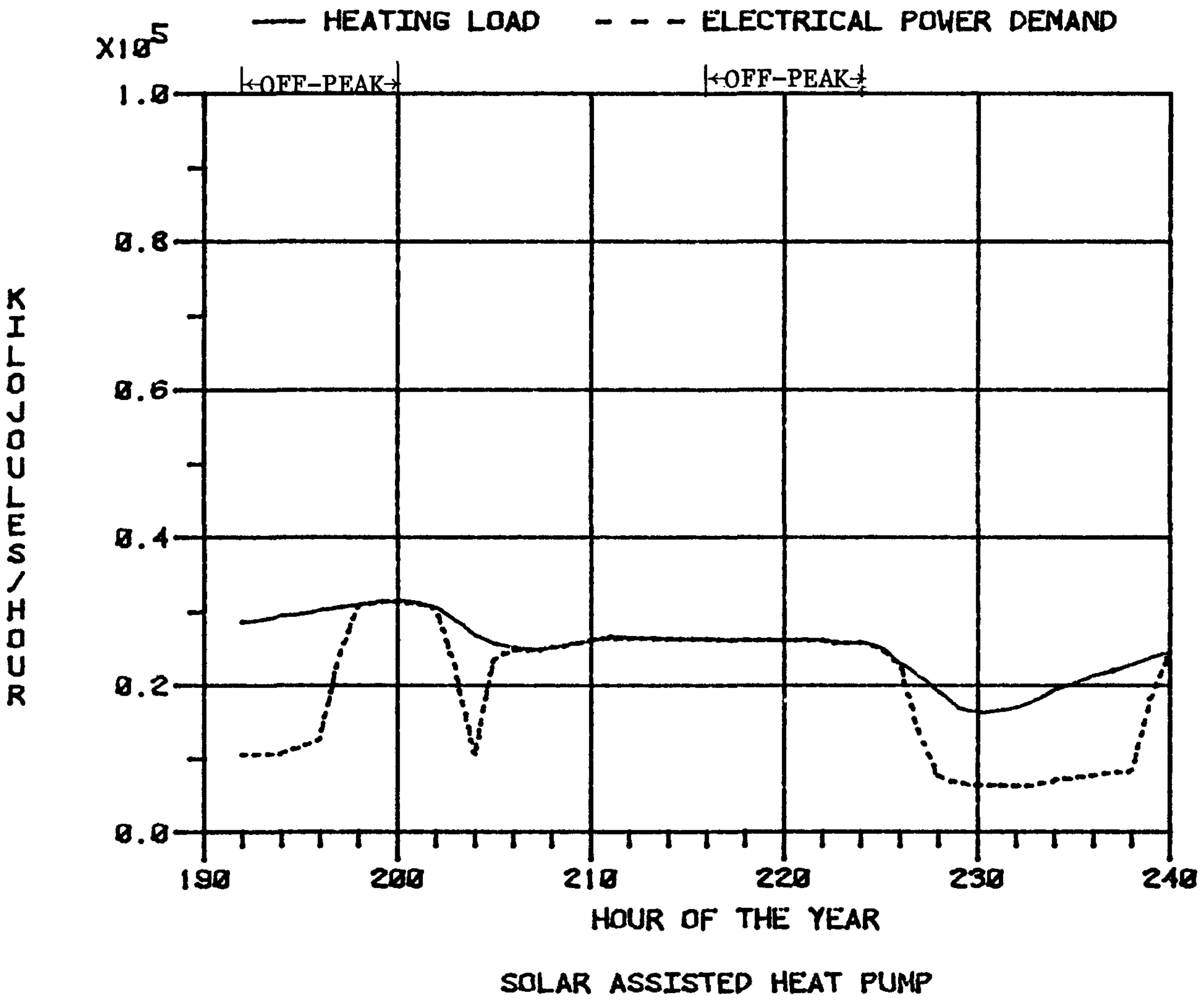

Figure 4-15. Electrical Energy Consumption of the Solar Assisted Heat Pump During the Peak Heating Load Period

4.2.9 Solar Assisted Heat Pump with Off-Peak Storage in the Solar Storage Tank

To reduce the peak load power demand, an electric resistance heater is added to the water storage tank of the solar assisted heat pump. During off-peak hours, the 36 kW/hr (123,000 Btu/hr) resistance heating coil is used to raise the storage tank temperature to 35°C (95°F) (the maximum operating temperature of the heat pump evaporator). A schematic representation of this system is shown in Figure 4-16.

The components of the solar system and the heat pump are identical to those used in the solar assisted heat pump discussed in Subsection 4.2.8.

Simulation Results

The electrical energy consumption of this system is 40 GJ (11,200 kWh) for the simulated heating season. This represents an 11% increase compared to the conventional air-to-air heat pump. The peak load power consumption of this system is plotted in Figure 4-17. As seen there, the electrical consumption at the peak load is 39 percent of the heating load. This is due entirely to operation of the heat pump compressor. Performance results for the solar collectors and storage tank are given in Table 4-5.

Table 4.5. Performance of Solar Components for Solar Assisted Heat Pump System with Off-Peak Storage

	GJ	Btu
Solar Radiation Incident on Collectors	132	(125×10^6)
Energy Delivered from Collectors to Storage	27.8	(26.2×10^6)
Collector Efficiency	21%	
Off-Peak Energy Input to Storage	17	(16.5×10^6)
Energy Lost from Storage	5.3	(5.0×10^6)
Storage Efficiency	89%	

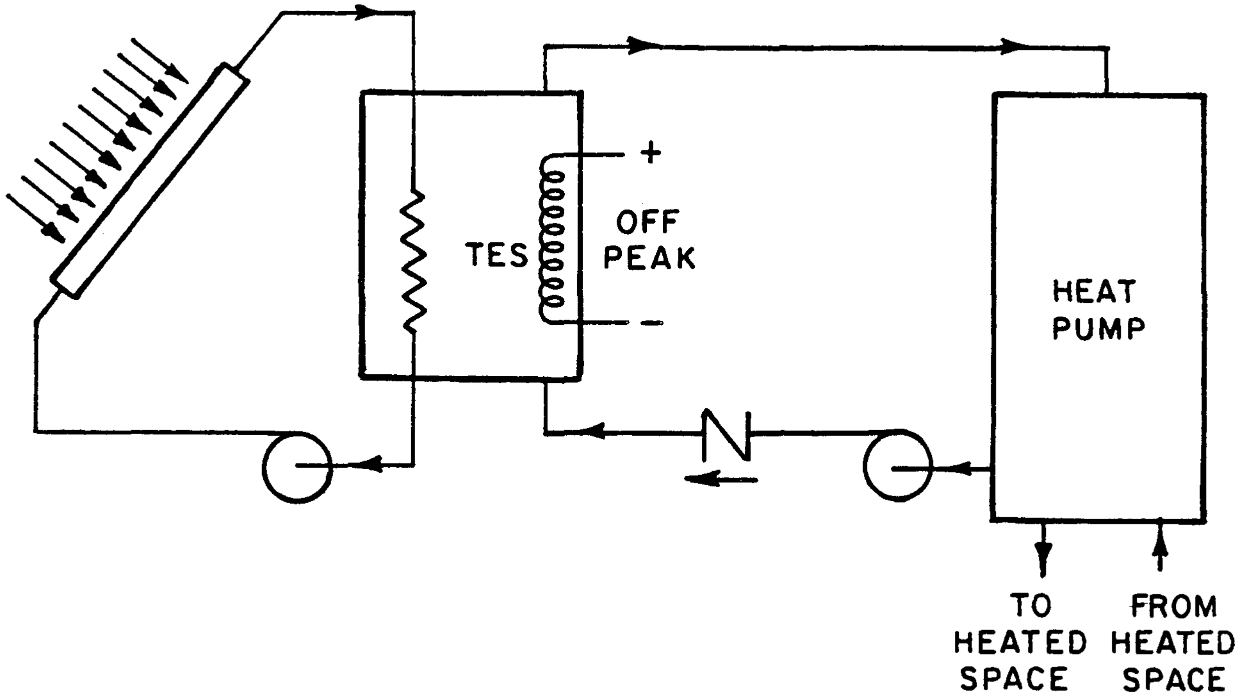

Figure 4-16. Solar Assisted Heat Pump with Off-Peak Storage in the Solar Storage Tank

4.2.10 Solar Assisted Dual Source Heat Pump with Direct Heating From Solar

In this system, a dual source heat pump is used in conjunction with a solar collection system to provide energy for space heating. The water source evaporator is connected to the solar storage tank from which it draws its energy during the water-to-water mode of operation of the heat pump. The second evaporator is an outdoor air coil used in the heat pump air-to-air mode. In addition, a water coil located in the hot air duct is connected to the solar storage tank to provide energy from the tank directly to the load. Back-up energy is provided by a resistance heating coil in the hot air duct. Figure 4-18 shows the system configuration.

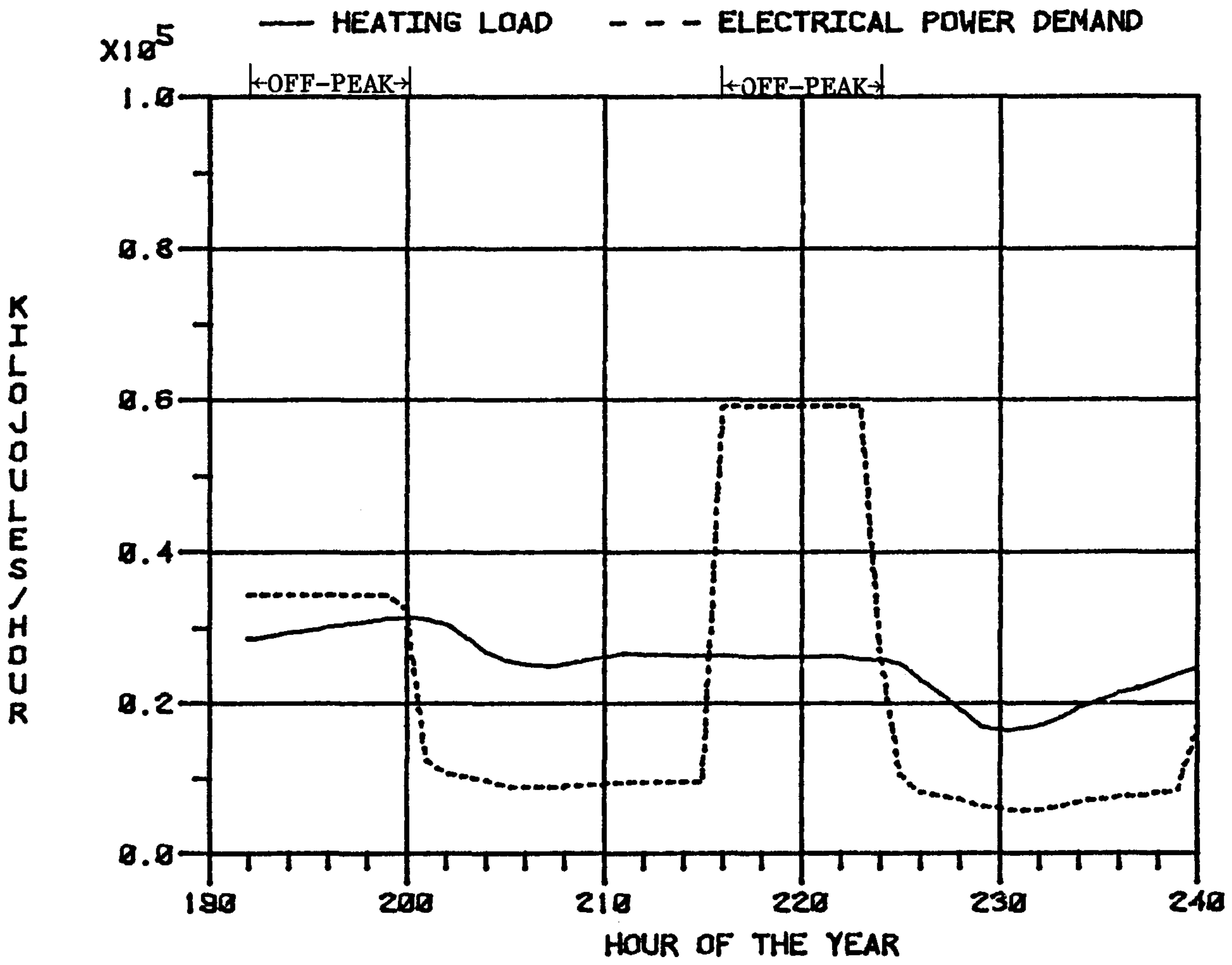

Figure 4-17. Electrical Energy Consumption of the Solar Assisted Heat Pump with Off-Peak Storage in the Solar Storage Tank During the Peak Heating Load Period

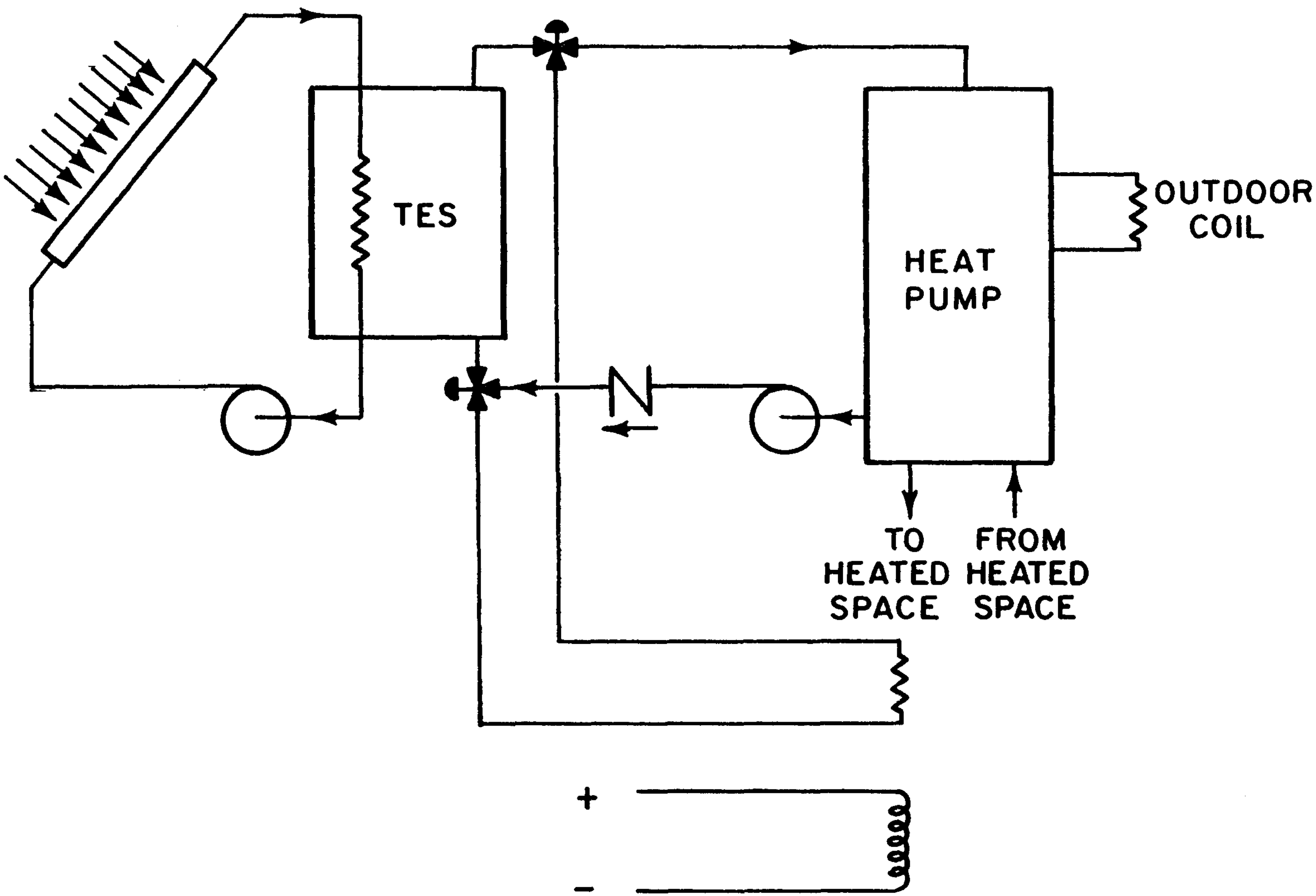

Figure 4-18. Solar Assisted Dual Source Heat Pump with Direct Heating from Solar

Components of the solar system (collectors, pumps, controllers and storage) are identical to those used in the conventional solar system described in Subsection 4.2.3. The dual source heat pump is identical to the one used in the heat pump with off-peak storage system described in Subsection 4.2.7.

Simulation Results

Electrical energy consumption of the system is 20 GJ (5,700 kWh) for the simulated heating season, a decrease of 25% compared to the conventional air-to-air heat pump. The SPF of this system is 3.12. Peak load electrical energy demand is plotted in Figure 4-19. This shows that the peak demand of 6.69 kW is 77% of the heating load and therefore contributes significantly to utility peak load. This demand is identical to that of the conventional air-to-air heat pump indicating the heat pump is in the air-to-air mode during the peak load period, and storage has been exhausted.

Table 4-6 list the performance results of the solar components in this heating system.

Table 4-6. Performance Results of Solar Components for Solar Assisted Dual Source Heat Pump with Direct Heating System

	GJ	Btu
Solar Radiation Incident on Collectors	132	(125×10^6)
Energy Delivered from Collectors to Storage	40	(37.6×10^6)
Collector Efficiency	30%	
Energy Loss from Storage	3.8	(3.6×10^6)
Storage Efficiency	9%	

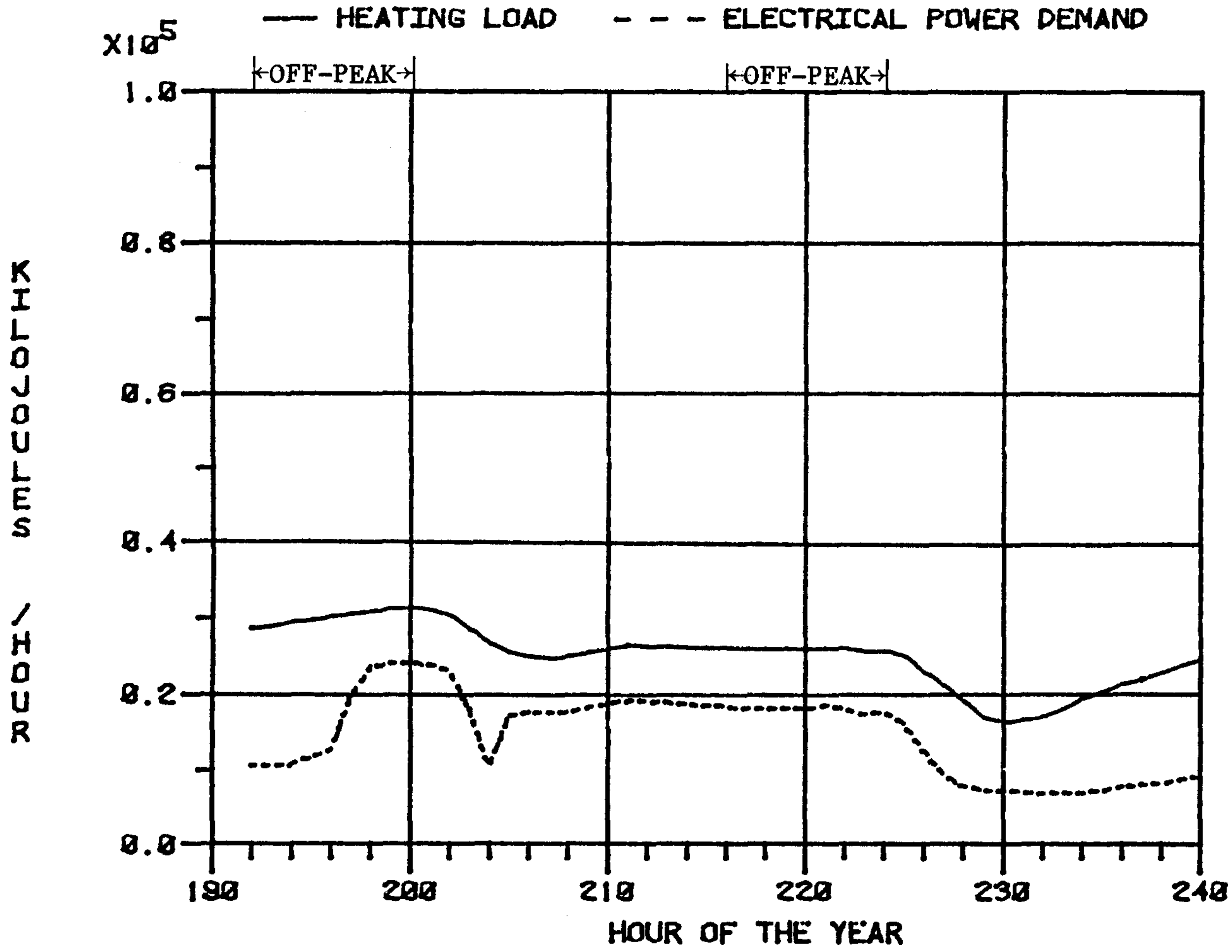

Figure 4-19. Electrical Energy Consumption of the Solar Assisted Dual Source Heat Pump with Direct Heating from Solar During the Peak Heating Load Period

The addition of the direct solar heating mode (bypassing the heat pump) in this system leads to a lower storage temperature and thus to more efficient collection of solar energy compared to the solar assisted heat pump system without direct heating (Section 4.2.9). With a lower storage temperature, the solar system efficiency is slightly higher (30% versus 27%) than for the system without the direct heating mode.

4.2.11 Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Energy Storage in the Solar Storage Tank

This system is identical to the solar assisted dual source heat pump with direct heating except for the addition of off-peak storage in the solar storage tank. A resistance heating coil is used to heat the storage tank to 35°C (95°F) during every off-peak period of the heating season. Figure 4-20 shows the configuration of this system. Details of the components used in this system are described in Subsection 4.2.10.

Simulation Results

Electrical energy consumption for this system is 24 GJ (6,700 kWh) for the simulated heating season, an 11% decrease compared to the conventional air-to-air heat pump. The seasonal SPF is 2.67. Peak load energy demand is plotted in Figure 4-21. It shows a reduction of 57% in peak demand compared to the electric resistance heating system. The performance of various components in this system is given in Table 4-7.

Here again we see that increased storage temperature due to off-peak charging causes a decrease in collection efficiency, from 30% to 23%, and a decrease in solar energy collected, from 40 GJ to 30 GJ, compared to the same system without off-peak storage (Subsection 4.2.10).

4.2.12 Solar Assisted Dual Source Heat Pump with Direct Heating and a Separate Off-Peak Storage Tank

In this system a separate off-peak storage tank is added to the solar assisted dual source heat pump system of Subsection 4.2.10. The 3.4 m^3 (900 gal) off-peak storage tank is heated to 35°C (95°F) during

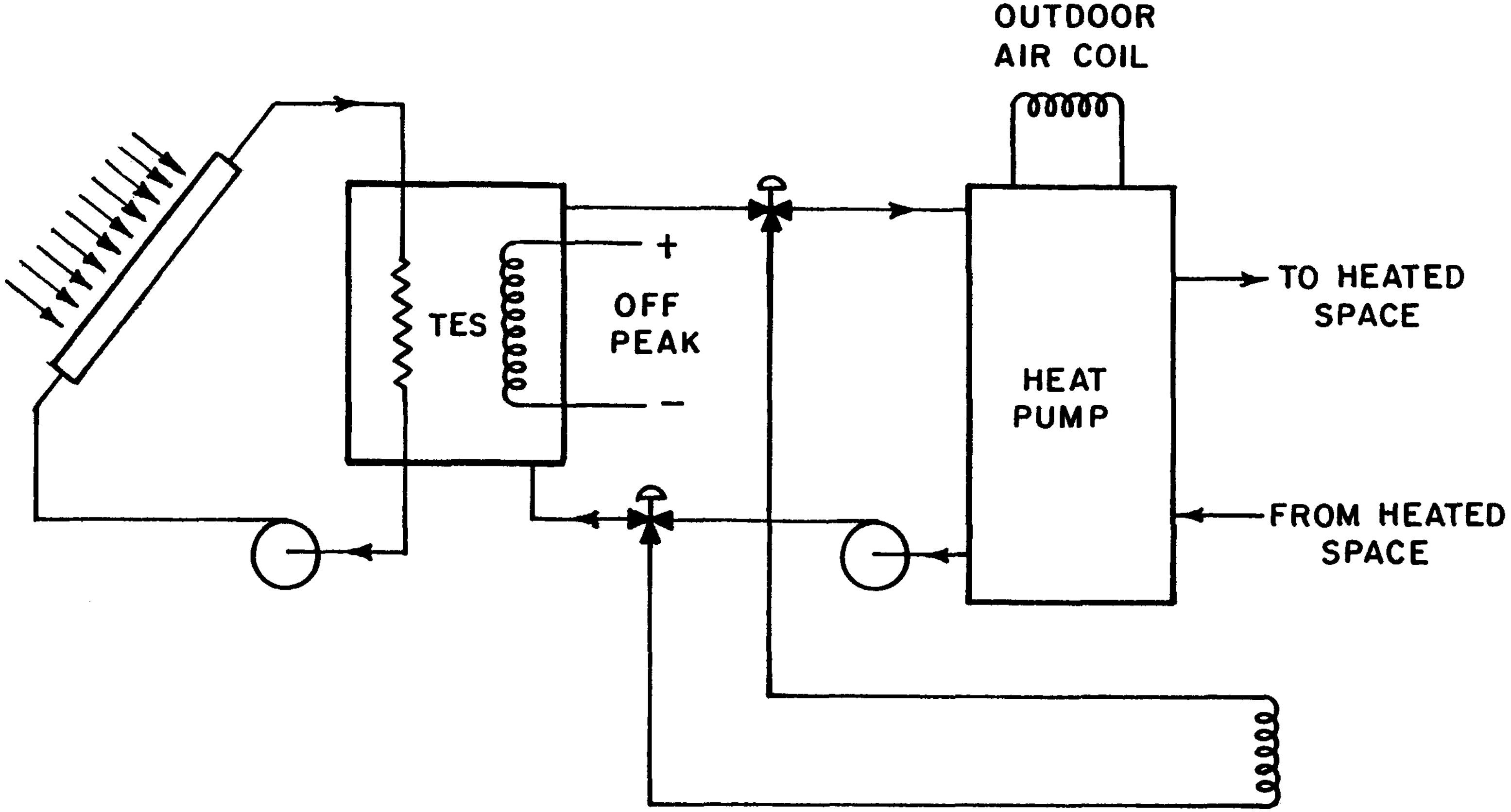

Figure 4-20. Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Energy Storage in the Solar Storage Tank

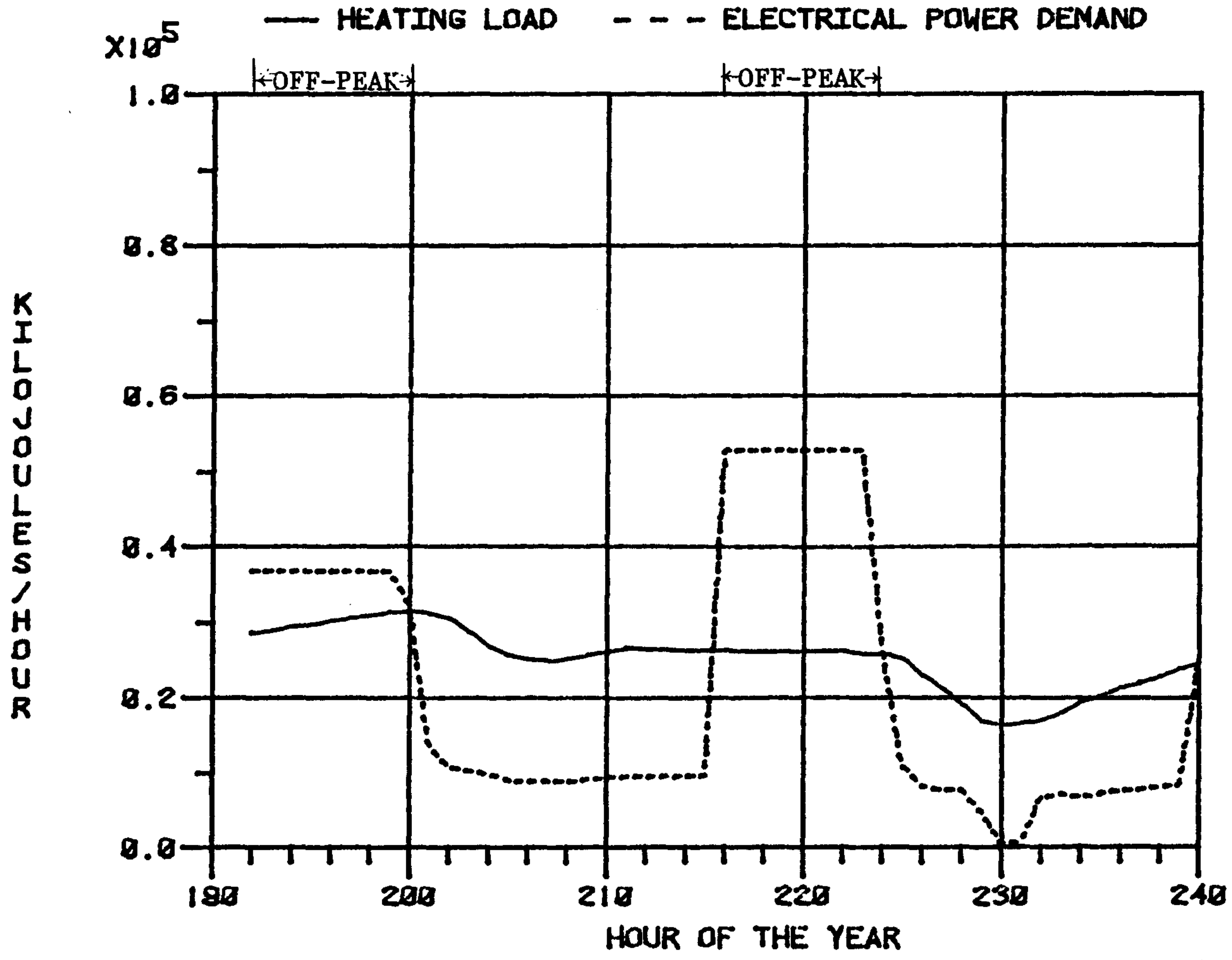

Figure 4-21. Electrical Energy Consumption of the Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Storage in the Solar Storage Tank During the Peak Heating Load Period

Table 4-7. Performance Results of Solar Components for Solar Assisted Dual Source Heat Pump System with Direct Heating and Off-Peak Storage In-Tank

	GJ	Btu
Solar Radiation Incident on Collectors	132	(123×10^6)
Energy Delivered from Collectors to Storage	30	(28.9×10^6)
Collector Efficiency	23%	
Auxiliary Energy Input to Storage	3.1	(2.9×10^6)
Total Energy into Storage	33	(31.8×10^6)
Energy Loss from Storage	5	(9.7×10^6)
Storage Efficiency	85%	

every off-peak period of the heating season. The remaining components of this system are identical to those of the solar assisted dual source heat pump with direct heating from solar described in Subsection 4.2.10. A schematic representation of this system is shown in Figure 4-22.

Simulation Results

Electrical energy consumption for this system is 25 GJ (6,900 kWh) for the simulated year, a decrease of 7% compared to the conventional air to air heat pump. This results in a SPF of 2.59.

Figure 4-23 shows the peak load energy consumption of this system. The peak demand of 3.07 kW is 35% of the heating load representing a substantial decrease from the 8.66 kW for the resistance heating system. Table 4-8 lists the performance of the various components of this system.

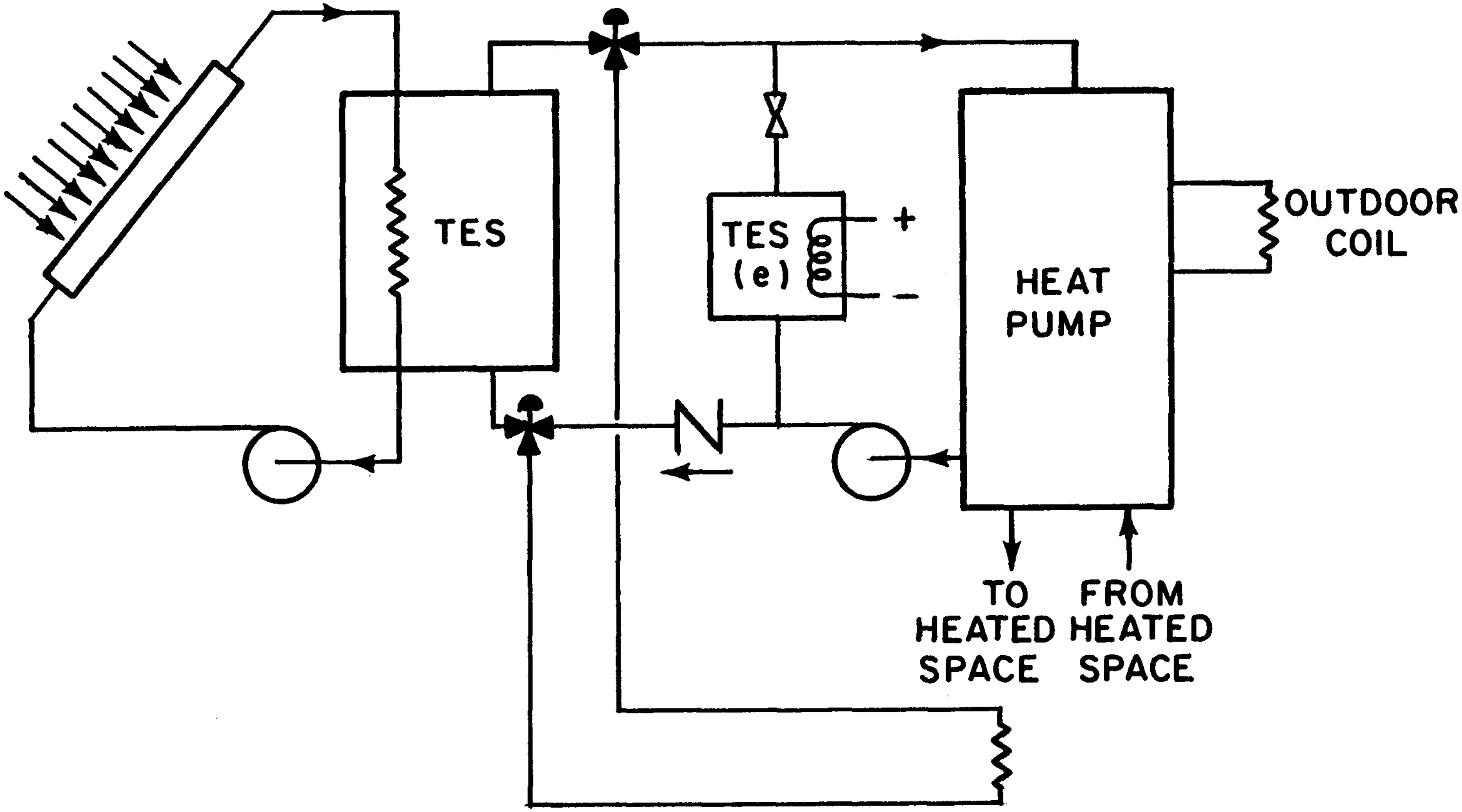

Figure 4-22. Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Energy Storage in a Separate Tank

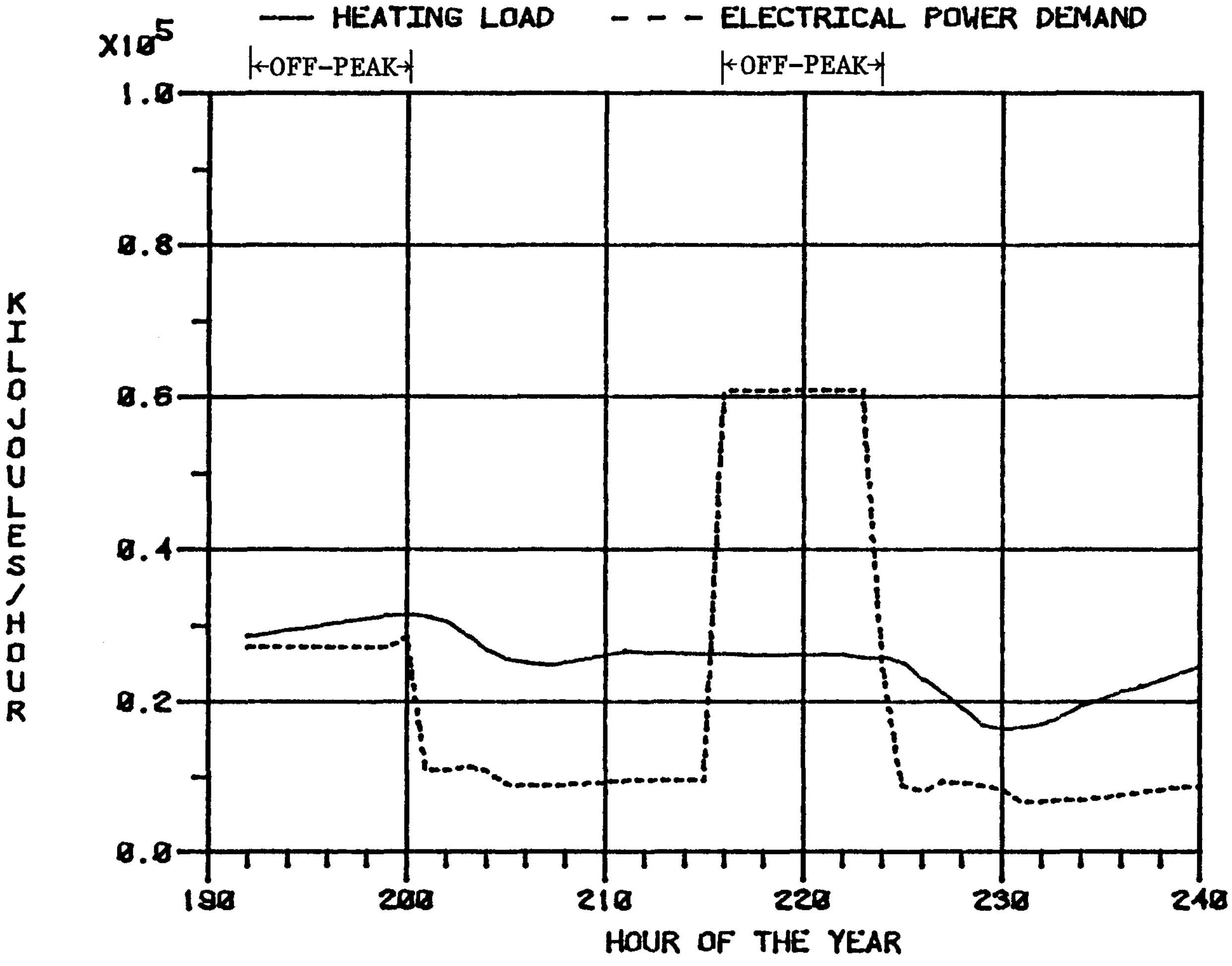

Figure 4-23. Electrical Energy Consumption of the Solar Assisted Dual Source Heat Pump with Direct Heating and a Separate Off-Peak Storage Tank During the Peak Heating Load Period

Table 4-8. Performance Results of Components for Solar Assisted Heat Pump with Dual Source, Direct Heating and a Separate Off-Peak Storage Tank

	GJ	Btu
Solar Radiation Incident on Collectors	132	(123×10^6)
Energy Delivered from Collectors To Solar Storage	34	(32×10^6)
Solar System Efficiency	26%	
Energy Loss from Solar Storage	4.5	(4.3×10^6)
Solar Storage Efficiency	87%	
Auxiliary Energy Input to Off-Peak Storage	7.1	(6.7×10^6)
Energy Loss from Off-Peak Storage	2.7	(2.6×10^6)
Off-Peak Storage Efficiency	61%	

4.3 ENERGY ANALYSIS OF SPACE COOLING SYSTEMS

4.3.1 Conventional Cooling System Energy Requirements

Conventional cooling system performance was simulated using the TRNSYS air source heat pump model. The peak cooling energy demand as calculated by TRNSYS was 8435 kJ (2.34 kW) and occurred on Sunday, August 25. However, weekend peaks are not a problem for the Philadelphia Electric Company. During 1968 the Philadelphia Electric Company experienced nearly identical weekday peaks on July 1 and July 18 at 3 PM daylight savings time (DST). The peaks as predicted by TRNSYS on July 1 and July 18 occurred at 3 Pm and 4 PM,respectively. The peak loads for the conventional system in the reference house as predicted by the Philadelphia Electric Company (PECo) and TRNSYS on July 1 and July 18, 1968 are shown in Table 4-9.

Table 4-9. Conventional Cooling System Hourly Peak Loads

	July 1	July 18
PECo	6152 kJ (1.71 kW)	6106 kJ (1.70 kW)
TRNSYS	6933 kJ (1.93 kW)	6364 kJ (1.77 kW)

The annual cooling energy requirements by the conventional system in the reference house were estimated to be 5.62×10^6 kJ (1562 kWh) by the Philadelphia Electric Company. The TRNSYS model was adjusted slightly (i.e., house thermostat setting) to arrive at an annual conventional cooling system energy use of 5.65×10^6 kJ (157 kWh), that agreed with the value derived by the Philadelphia Electric Company.

4.3.2 Conventional Solar Air Conditioning (A/C) System

A schematic diagram of this system is shown in Figure 4-24. The system has 55.8 m^2 (600 ft^2) of collector area. The solar storage tank has a capacity of 4.5 m^2 (1200 gal). The solar A/C is a lithium-bromide absorption chiller with a capacity of 25,315 kJ/hr (2 tons). The operation of this system is discussed in Appendix B.

Simulation Results

An absorption chiller is activated by thermal energy supplied to its generator. The thermal energy supplied to the chiller during the cooling season is 25.6 GJ (24.2×10^6 Btu). Of this total, 81.4% is supplied by solar energy. The remaining 4.8 GJ (4.5×10^6 Btu) is supplied by the auxiliary electric heater. The energy used by pumps and fans is 2.8 GJ (770 kWh). Total electricity usage is 7.5 GJ (2093 kWh). The seasonal performance factor (ratio of the cooling load to the thermal input to the absorption chiller) is 0.666. The ratio of the cooling load to electricity usage is 2.266 as compared to the value of 2.90 for the conventional vapor compression air conditioner.

On July 1, the peak electric demand by the solar air conditioner is only 0.49 kW as compared to 1.93 kW for the vapor compression unit.

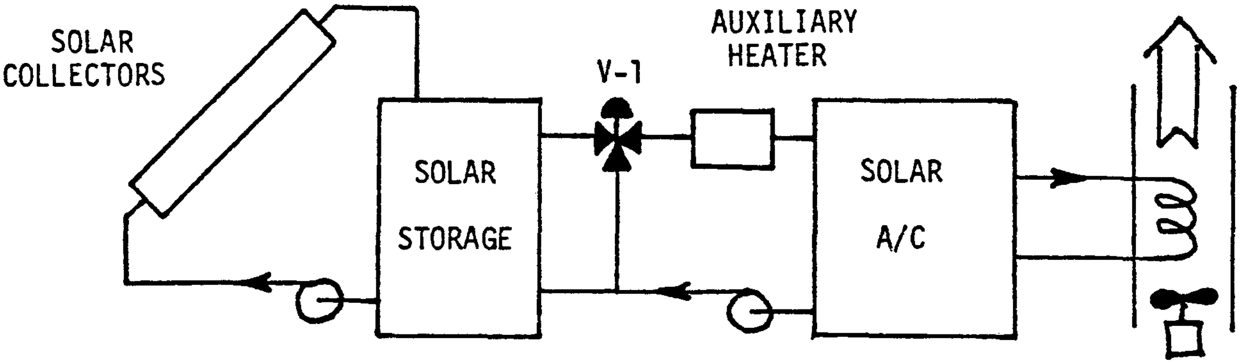

Figure 4-24. Conventional Solar A/C

However, on July 18, the peak demand by the solar system is 4.05 kW as compared to 1.77 kW for the conventional air conditioner. In each case, these are the peak electric demands during the on-peak period (8AM - 12PM). The seasonal peak for the solar air conditioning system is 5.62 kW and occurs at 3PM on July 15.

The seasonal performance of the solar components is shown in Table 4-10.

Table 4-10. Performance of Solar Components for the Conventional Solar Air Conditioning System

	GJ		Btu x 10^6
Solar Radiation Incident on Collectors	133		126
Energy Delivered from Collectors to Storage	22.9		21.7
Collector Efficiency		17.2%	
Energy Lost from Storage	1.7		1.6
Storage Efficiency		92.6%	

4.3.3 Solar Air Conditioning System with Off-Peak Chilled Water Storage

A schematic diagram of this system is shown in Figure 4-25. The system is the same as the one described in Subsection 4.3.2 with the exception that a 4.5 m^3 (1200 gal) chilled water tank acts as a buffer between the absorption chiller and the conditioned space. The auxiliary heater is disabled during the on-peak period (8AM - 12PM). During the offpeak period, the auxiliary electric heater is used to operate the absorption chiller to cool the chilled water storage to a preset temperature. The operation of this system is discussed further in Appendix B.

Simulation Results

The seasonal thermal energy demand by the absorption chiller is 32.1 GJ (30.5 x 10^6 Btu) of which 77.5% is supplied by solar energy. The remaining 7.2 GJ (2009 kWh) is supplied by the auxiliary electric heater. The various pumps and fans in the system use 2.1 GJ (584 kWh) during the cooling season. Total electricity usage is 9.3 GJ (2593 kWh). The seasonal performance factor is 0.531 and the ratio of the cooling load to seasonal electricity usage is 1.828.

This system does not use the auxiliary heater during the on-peak period. During this time, electricity is only used for pumps and fans (typically 0.41 kW). During the offpeak period, however, the peak electric demand may be significant. For example, on July 18 the average electric demand during the offpeak period was 4.24 kW.

The seasonal performance of the solar system components is shown in Table 4-11.

4.3.4 Solar Air Conditioning System with Off-Peak Hot Water Storage

A schematic diagram of this system is shown in Figure 4-26. The system is the same as that described in Subsection 4.3.2 with the exception that the auxiliary electric heater does not supply thermal energy directly to the absorption chiller but is used during offpeak periods to

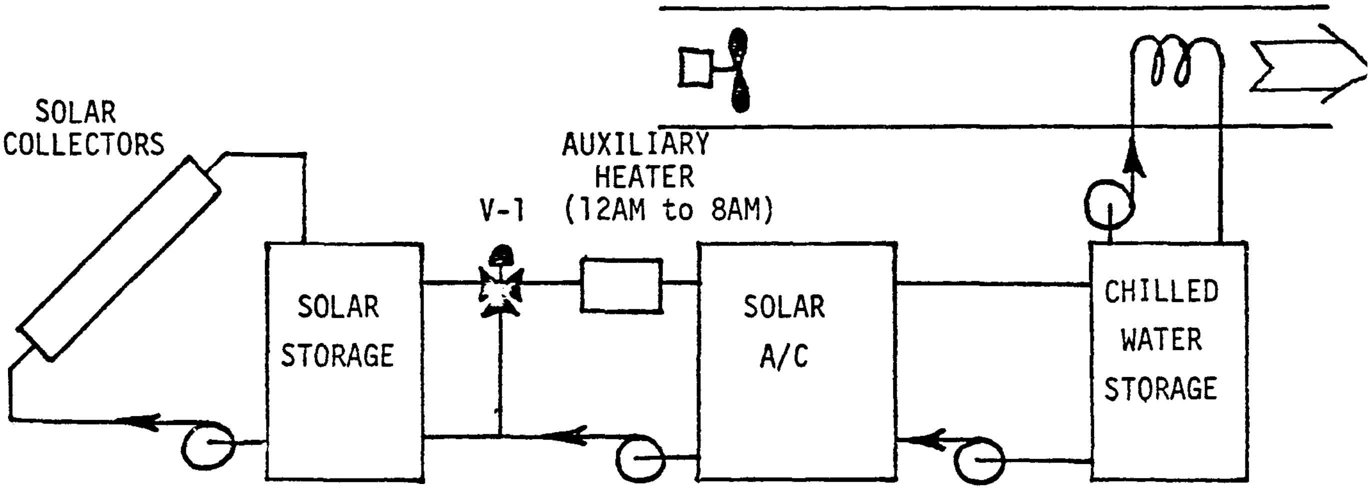

Figure 4-25. Solar A/C with Off-Peak Chilled Water Storage

Table 4-11. Performance of Solar Components for the Solar Air Conditioner with Off-Peak Chilled Water Storage

	GJ		$\text{Btu} \times 10^6$
Solar Radiation Incident on Collectors	133		126
Energy Delivered from Collectors to Storage	26.5		25.1
Collector Efficiency		19.9%	
Energy Lost from Solar Storage	1.8		1.7
Solar Storage Efficiency		93.2%	

charge a 2 m^3 (533 gal) hot water storage tank. Refer to Appendix B for a further discussion of this system.

Simulation Results

The thermal energy demand by the absorption chiller during the cooling season is 25.6 GJ (24.3×10^6 Btu) of which 79.6% is supplied from solar energy. The offpeak hot storage supplied 4.9 GJ (4.7×10^6 Btu)

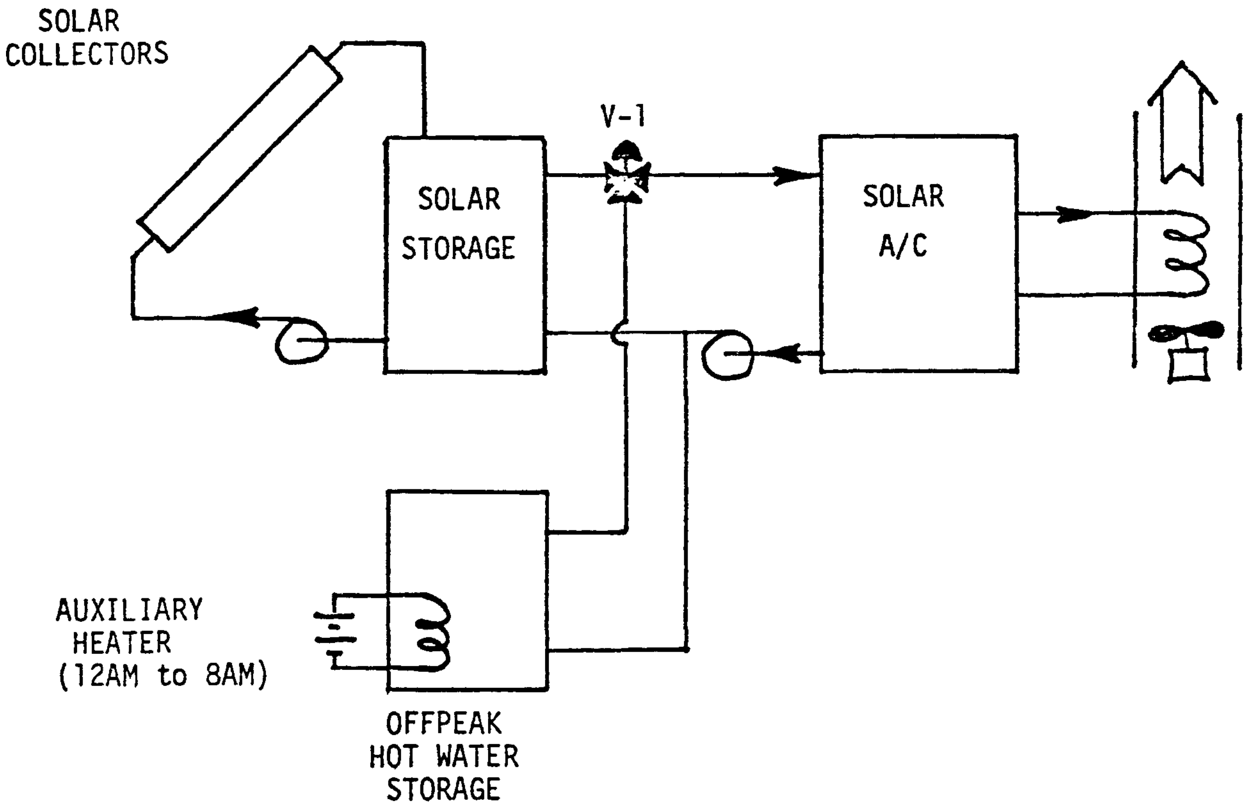

Figure 4-26. Solar A/C with Off-Peak Hot Water Storage

to the chiller. Pumps and fans use 3.05 GJ (848 kWh), and 6.2 GJ (1724 kWh) are used to charge offpeak storage. The total seasonal electric energy usage is 9.3 GJ (2572 kWh). The seasonal performance factor is 0.668 and the ratio of cooling load to electricity usage is 1.814.

This system, like the one with offpeak chilled water storage does not use a significant amount of electric energy during the on-peak period. Typically, the electric demand by pumps and fans during this period is 0.49 kW. The maximum average demand during an offpeak period was 7.73 kW and occurred on July 16. This high demand was due to the hot storage having been depleted on the previous day.

The performance of the solar components is shown in Table 4-12.

Table 4-12. Performance of Solar Components for the Solar Air Conditioner with Off-Peak Hot Water Storage

	GJ		Btu x 10^6
Solar Radiation Incident on Collectors	133		126
Energy Delivered from Collectors to Storage	22.4		21.2
Solar Collector Efficiency		16.8%	
Energy Loss from Solar Storage	1.7		1.6
Solar Storage Efficiency		92.3%	
Energy Loss from Offpeak Storage	1.2		1.16
Offpeak Storage Efficiency		80.2%	

5. EFFECT ON ELECTRIC UTILITY IN PHILADELPHIA, PA

5.1 DEFINITION OF SOME ELECTRIC UTILITY TERMS*

For readers not familiar with electric utility terminology, definitions of some of the terms used in this report are given below.

Electric utility companies are regulated monopolies; in return for exclusive franchises in their service area, utility companies' rates and service standards are subject to approval by a government regulatory authority, usually a state regulatory commission. In addition to compensation for all costs incurred, share-holder owned utilities are permitted an appropriate rate of return on a certain part of their investment, called the rate base. The rate base is a value established by a regulatory authority which generally represents the amount of property used and in useful service.

The rate per unit time at which a customer uses electric energy is called demand or load. This demand may be instantaneous or averaged over a certain time period: 15 minutes, 1 hour, 1 day, 1 year. A kilowatt (kW) is a measure of the demand for electricity. One thousand kilowatts equal one megawatt (MW) or one million watts. Energy use is measured in kilowatt-hours (kWh). For example, an appliance may require 0.2 kW to operate and, if this appliance operates for one hour, the electric energy used will be 0.2 kWh. One kWh equals 3412 Btu.

Peak demand is the highest demand that occurs within a specified period of time. The annual system peak is the highest total hourly demand experienced by a utility system during a year. If that peak occurs consistently in the summer (or winter), the utility is called summer peaking (or winter peaking). Monthly system peaks and daily system peaks are also important to utility generation operations. Class peaks are peak loads for certain classes of customers: residential, industrial, commercial. The residential class peak, for example, would be the highest reading of a single meter to which all residences of a

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*This Section is taken from a previous report by the Franklin Research Center (Ref. 5-1).

utility are connected. Class peaks are important to utility distribution operations. An off-peak load is a load that does not occur during the system and/or the class peak hours.

Since electric utilities serve a great number of customers simultaneously, the peak demands of all customers do not occur at the same time. Thus, a single all-electric home may have a connected load of 15 kW; this is the sum of the power ratings of all pieces of electric equipment in the home. All lights, appliances, and electric heaters are seldom, if ever, turned on simultaneously in a home. Thus, the individual, instantaneous peak demand of the home may never be more than 13 kW. Most utilities design their systems on the basis of a one-hour peak demand. That is the highest average load over a one-hour interval. It is always smaller than (or, at most, equal to) the instantaneous peak.

The diversified demand per customer of a group of customers is defined as the peak demand of the group divided by the number of customers. It is always lower than the individual customer's peak demand because not all customer peak demands occur simultaneously. This is readily apparent when one realizes the time difference in getting up, cooking meals, doing laundry, or entertaining in different homes. It is less readily apparent for the heating demands of a group of identical homes on a cold day, a fact well-known to utility operators and amply documented (i.e., Refs. 5-2, 5-3, 5-4).

Integrated system demand is the summation of the continuously varying instantaneous demands of all the customers of a utility during a given time period. By definition, this is a diversified demand.

Most electric utility residential rate structures incorporate an energy charge only; the customer pays according to the number of kilowatt-hours used during the billing period. The rate per kWh, however, may vary with the amount used during the billing period. Most commercial and industrial rate structures consist of both a demand charge and an energy charge. In addition to paying for the number of kilowatt-hours used during the billing period, the customer also pays a "demand" charge which depends on his own peak demand (maximum kW) during the billing period or during the preceding year. In some cases, the energy charge is a function of the peak demand; a customer with a high peak demand also pays a higher energy charge.

Other terms are defined where they occur.

Since the peak electrical power demands of all customers of a particular class do not occur at the same time, the peak demand of a group of customers (the "diversified demand") is less than the sum of the individual demand peaks. This is explained on the previous page. Because of the diversity phenomenon, the effect of solar heating on an electric utility system cannot be evaluated by determining the energy "displaced" by solar energy alone. Rather, the diversified electrical demand of the projected number of solar homes must be added to all other demands on the electrical network, and the effect of that integrated electrical demand on the system must be evaluated.

5.2 UTILITY SYSTEM MODELING

5.2.1 Rationale

In order to obtain the best evaluation of the effect on an electric utility of the presence of a large number of solar heating/cooling systems, it is not sufficient to model an individual building and to determine its change in energy consumption. Since solar heated/cooled homes have different energy requirements from conventionally heated homes during different hours of the day, the presence of a large number of such homes may require changes in the generation pattern of a utility. The resultant changes in costs to serve these solar customers cannot be evaluated by merely determining the reductions in energy consumption of the solar home with respect to the conventional home and multiplying them by the average energy cost of the conventional home (which is the most common method of analysis). It is somewhat more accurate to multiply these savings by the marginal cost to the utility of serving these homes (Ref. 5-5). This will give a reasonably good results when the number of solar customer on the utility is small, because the utility's method of generation and dispatching power will not be changed. When the number of solar buildings is sufficiently large to affect these patterns, however, even this method of analysis is insufficient. What has to be done is to consider the utility's entire network as a whole and to compare the behavior of the present utility system with a system in which a large number of conventionally heated buildings are replaced by solar heated/cooled buildings. This is the method used in this project.

5.2.2 Diversified Demand Analysis

In Section 4, the hour-by-hour electrical energy consumption for the representative home equipped with different heating and/or cooling systems were determined. The simulation for the conventional systems was adjusted so that the total daily energy consumption matched the diversified total daily energy consumption obtained from actual measurements by the Philadelphia Electric Company (PECo).

The diversified hourly energy demands for the solar systems was obtained by assuming that the ratio of the diversified to the simulated hourly energy demands of solar systems is the same as for conventional system. The number of solar heated homes and the performance data available from them is insufficient to permit a statistical determination of the diversity of solar heated homes. Therefore, the above assumption is the best that can be made until statistics on the operational performance of large groups of solar homes become available.

The same procedure was followed with respect to solar air conditioned homes.

5.2.3 Market Penetration of Solar and Off-Peak Storage Systems

In a previous study, a market penetration analysis for solar heated homes was performed in 1976 for the Philadelphia Electric (PECo) service area (Ref. 5-1, Section 4.1). Its results are presented in Table 5-1 and in Figure 5-1. These projections are probably conservative, i.e., low. However, electric heating is not very common in the PECo service area because new gas hookups have always been available within the City of Philadelphia (where it is provided by a municipal utility, the Philadelphia Gas Works), and new gas hookups have been resumed in the suburbs (where it is provided by PECo) after a moratorium of a few years.

An updated market penetration analysis was not performed because it was not required for the purposes of the present project. When the penetrations of solar homes were varied from 0% to 100% in the Ref. 5-1 study, the marginal costs per solar home varied less than 10% from the costs obtained for the probably forecast of solar homes (Table 5-1 and Figure 5-1). The results obtained from a systems model using 100% penetration are therefore valid, even if actual penetrations of solar heated homes will be significantly smaller. A 100% penetration of solar and/or off-peak storage equipment was therefore used in all PECo system investigations.

Table 5-1 Low, Probable, and High Forecasts of Solar Heated Single-Family Homes on PECo System (from Ref. 5-1)

Year	Number on System in Stated Year					
	Conventional Solar Heating			Solar Assisted Heat Pumps		
	Low	*Probable*	*High*	*Low*	*Probable*	*High*
1980	50	75	150	0	0	0
1985	400	800	1200	100	200	300
1990	750	2400	3450	450	1800	2550
1995	1300	4150	6150	1700	5850	8850
2000	1600	5350	8000	4400	16,650	25,000

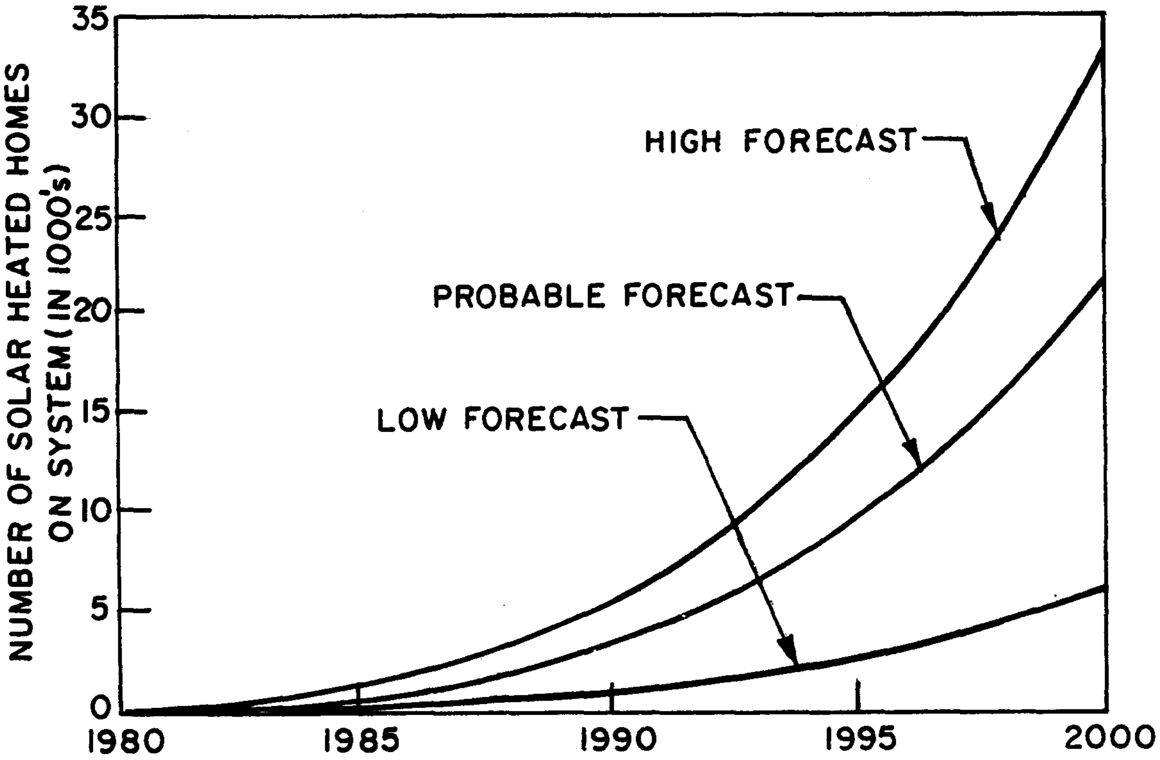

Figure 5-1. Low, Probable, and High Forecasts of Solar Heated Single-Family Homes on Philadelphia Electric Co. System (from Reference 5-1)

5.2.4 Procedural Details

a. Summary

The results of the diversity analysis (see Section 5.2) were combined with a 100% market penetration starting in the year 1980 to obtain the total residential heating (cooling) load for each of the space conditioning systems studied. This information was combined with adjusted basic system load modesl (BSLM) for the years 1985 and 1995 to form total system load models (TSLM) representing the entire Philadelphia Electric (PECo) system. The production costs for each of the load models were calculated by a computer program that simulates the operation of each of the generators on the Philadelphia Electric system on a bi-hourly basis throughout the year. From these production costs, an economic evaluation of the effect of solar heating on the Philadelphia Electric generation system was performed. The 1968 load model was chosen as the basis for this analysis because the 1968 weather pattern had been used to determine the energy consumption of the typical home for heating and air conditioning (see Section 4.1).

b. System Load Model Without Residential Heating Component

The basic system load model without residential heating was derived from the 1968 actual hourly system loads on the PECo system with the estimated hourly home heating and cooling load components removed to eliminate the model's temperature-dependent load. This load model was normalized by dividing each hourly load by the 1968 annual peak load to form a normalized basic system load model without residential heating or cooling. The basic system load models for the years 1985 and 1995 were constructed by multiplying the normalized basic system load model by the projected peak loads for those same years. The load models were corrected so that the annual energy consumption was within .2% of the forecast. The correction was made to each hourly load by use of the following equation:

$$L_c = P_p - a\ (P_p - L_u) \qquad (5\text{-}1)$$

where L_c = corrected hourly load
P_p = projected peak load
L_u = uncorrected hourly load
a = $(8760\ P_p - E_p)/(8760\ P_p - E_u)$
E_p = projected annual energy consumption
E_u = uncorrected annual energy consumption.

c. Residential Load Models

The residential load models for each of the alternate heating/cooling system were obtained as described in Sections 4. and 5.2.

d. Total System Load Model

The total system load models were obtained by adding multiples of the residential load models, corresponding to 100% market penetration, to the basic system load models without residential heating and cooling. The total system load models represent the PECo system with contribution of each type of alternate heating/cooling system assuming 100% penetration in all new single-family homes constructed from 1980 to the year studied: 1985 or 1995.

The total system load model with conventional resistance heating was used as the base case for the years 1985 and 1995. Production costs for all the total system load models corresponding to all the alternate heating/cooling systems used were calculated by a computer program called PRODCOST. PRODCOST (Ref. 5-6) simulates the dispatch of generators on the PECo system on an incremental operating cost basis. The program accounts for maintenance and forced outages, start-up costs, and dispatch of limited energy (hydro-electric and pumped storage) generation. The annual fuel and operating costs were calculated from the PRODCOST simulated economic dispatch. Table 5-2 shows the escalation of fuel prices used in the production cost calculations.

Table 5-2. Projected Fuel Costs (¢/Million Btu)
Philadelphia Electric Company

Year	Coal	Oil	Nuclear
1979	150*	425*	30*
1985	230	675	50
1995	500	925	140

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*Actual Costs

5.3 ANNUAL PRODUCTION COSTS AND MARGINAL COST SAVINGS

The complete system of the Philadelphia Electric Company was modeled under the conditions of "economic dispatch" which is the normal mode of operation of that utility. At any hour of the day, all generation units are operated in such a manner as to minimize the marginal cost of additional generation. This means that, when an additional increment of power is required, the generator which can provide that power at the lowest increase in cost will be called upon to furnish ("dispatch") that power. This method of economic dispatch is the normal operating mode of this (and most) utility subject to certain operational constraints pertaining to the rate at which power can be increased for each particular units, minimum reserve requirements, and air pollution limitations. The system was modeled under the assumption that all additional customers starting in the year 1980 would equip their homes with a particular type of space heating/cooling unit, conventional, solar, with or without off-peak storage. The PECo network was then modeled for each of the 8760 hours of the year assuming economic dispatch throughout, 1985 and 1995, using the generation units planned to be in service in those years. The total production costs of the utility for each of these years were then compared. Data for the base system (electric resistance heating and compression air conditioning) are shown in Table 5-3. The changes in production costs when alternate heating/cooling systems were used were then determined and divided by the number of homes assumed to be equipped with the alternate heating/cooling systems in the respective years: 34,400 for 1985 and 66,000 for 1995. The result is the true marginal cost of energy if a conventional heating/cooling system is replaced by an alternate system in a single residence.

Table 5-3. Base System Data

Item	1985	1995
Total Production Costs (million $)	950	1882
Number of New Customers*	34,400	66,000
Average Production Cost (¢/kWh)	2.87	4.36
Average Production Cost per Residential Customer ($)	558	847

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*The number of new customers is the number of single-family homes added to the PECo system between 1980 and the year shown.

These results are shown in Table 5-4. The costs shown are essentially for fuel only; no capacity credit is taken into account. Since PECo is in a no-growth or slow-growth mode, the validity of capacity credits may be questioned.

Philadelphia Electric Company, a utility in an industrial area, sells less than 30% of its energy to the residential market. As a consequence, even the 100% market penetration assumed in this study would not affect the company's generation or transmission planning for the next 25 years at least. Residential distribution systems are currently designed for summer peaks except in areas of large concentrations of electrically heated homes, where they are designed for winter peaks. The peak demands of the conventional electrically heated homes and the solar heated homes are identical (see Section 4.2.3). As a result, the design of the distribution system will remain the same independent of the number of electrically heated homes that employ solar assisted heating.

Table 5-4. Annual Electric Production Cost Comparison
Philadelphia Electric Company

Heating/Cooling System	Customer Annual Energy Consumption (kWh)	Annual Energy Savings per Customer (kWh)	Utility Cost Avoidance Per Customer ($)	
			1985	1995
Resistance Heating	19428	Base	Base	Base
Conventional Solar Heating	12308	7120	510	480
Solar Heating with Separate Off-Peak Storage (2 Tanks)	14508	4920	450	410
Conventional Air-to-Air Heat Pump	9158	10270	750	860
Solar Assisted Dual Source Heat Pump w/Direct Heating from Solar	7238	12190	900	1050
Conventional Solar Heating, Solar Air Conditioning	12824	6604	470	430
Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Cold Storage (2 tanks)	15524	3904	420	370
Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Hot Storage (2 tanks)	15502	3926	420	370

Notes:
Unless otherwise specified, all systems contain conventional electric air conditioning (A/C). Solar air conditioning units are absorption systems. All energy data are for space heating and cooling only.

The energy cost for the conventional electrically heated and cooled home (base home) is $558 in 1985 and $847 in 1995 (Table 5-3). The marginal cost avoidance for many of the solar and storage systems is larger than these amounts. This means that the utility avoids generation costs in excess of the cost of furnishing space heating/cooling energy to the base home. It would, of course, be incorrect to assume that these savings could be passed on to the individual building owner, since they are not true "savings" to the utility but merely a "cost avoidance." However, the benefits of this cost avoidance are passed on to *all* customers of that utility in the form of lower fuel charges. This can provide a rationale for the introduction of special tariffs to solar building onwers which are sometimes called "subsidies" (Ref. 5-1, p. 9-3). These cost avoidances benefit all utility customers and therefore, virtually society as a whole, therefore, they should be used in considering national policy. The cost saving that can be passed on to the solar homeowner, however, must be determined on the basis of *average* costs and not *marginal* costs since, generally, consumers pay the average costs of products and not their marginal costs. It is probably impossible, and would certainly inequitable, for a utility to negotiate a tariff with an individual that reflects its marginal rather than its average cost. Average cost savings accruing to PECo from solar systems are determined in Section 6.

5.4 EFFECT OF UTILITY INTERCONNECTION

The results of Section 5.3., like all the results presented in this report, are based on the behavior of the network of a single utility assuming that this utility is a self-contained entity. Actually, this is not the case. All individual utilities in the United States are interconnected to neighboring utilities which are joined to larger entities and are operated as larger operating units. The Philadelphia Electric Company, for example, is a member of the Pennsylvania-New Jersey-Maryland Interconnection (PJM) which fully integrates the bulk power generation and transmission operations of eleven electric utilities serving 21,000,000 people in a 50,000 square-mile territory extending from nothern New Jersey to Washington, D.C. Through the constant interchange of electricity, this integrated operation offers greater reliability and economy than would be possible if the bulk power systems of these same companies were developed and operated independently.

PECo is also a member of the Mid-Atlantic Area Council (MAAC) which is made up of the eleven PJM companies and several municipal and cooperative electric ompanies operating within the PJM service area. MAAC's purpose is to further augment the reliability of the bulk electric systems of its service through a higher degree of coordinated planning of their generation and transmission facilities. The National Electric Reliability Council (NERC) consists of eight regional entities like MAAC which develop coordinated planning of inter-regional bulk electric transmission systems so that the reliability of service can be maintained throughout the United States and a part of Canada.

In practice, the Philadelphia Electric Company does not operate according to economic dispatch for its own network alone, but all units of the PJM Interconnection are dispatched economically from a central control station located in Valley Forge, PA. Therefore, on a short-tun basis (Ref. 5-7), the marginal cost analysis of Section 5.3 is not correct since, in day-to-day operation, PECo does not only call upon its own generation units to satisfy its customers' demands, but has access to all of the approximately 400 units within the PJM system. The result is a flattening of the marginal cost curve plotted as a function of power level. For short-run effects, the marginal cost savings calculated in Section 5.3 are higher than the true cost avoidances that would be experienced by PECo if the specified alternate space conditioning systems were suddenly installed by its customers. In the long run, however, the individual utilities of the PJM Interconnection install the generation capacity appropriate to their loads. It is, therefore, believed that the analysis presented is valid because it yields a correct picture of the long-run cost avoidances that would accrue to the utility if its customers installed these alternate systems; for purposes of national policy planning, it is the long-run effects that must be considered.

6. ENERGY/COST PERFORMANCE IN PHILADELPHIA, PA

6.1 UTILITY COST COMPONENTS

The costs to serve residential customers having different conventional or solar heating systems with or without off-peak storage were determined on a cost allocation basis used by the Philadelphia Electric Company to justify its rates to the State Public Utility Commission. These costs are generally made up of three major items: demand related costs, customer related costs, and energy related costs.

In the PECo cost allocation method, demand related costs are made up of three components:

> Costs related to class peak. Class peak is the diversified peak demand of all residential customers of that utility. Due to diversity of demand, the class peak is lower than the sum of the individual customers' maximum demands. These costs primarily represent costs of the local distribution network.
>
> Costs related to individual customer maximum demand. These costs pertain to the costs of installing a line to the individual home.
>
> Costs related to contribution to system peak. These costs essentially represent the capital costs of installing generation and transmission capacity. Although these facilities may be used only infrequently, they must be amortized over a fixed life-time.

The demand related costs used are PECo costs for the year ending March 31, 1980 escalated at a rate of 8 percent per year. The class peak for electric heating customers occurs in the winter. Therefore, the contribution to class peak on the part of the systems investigated are their contributions to the winter residential peak which occurs in mid-morning. This value was determined to be 9.16 kW made up of an electric resistance heating demand of 8.66 kW and a house fan power demand of 0.5 kW. The diversified demand of the conventional heat pump system is 1.97 kW less. The off-peak storage systems are timed so that they do not contribute to the winter residential class peak except for 0.13 kW for the storage pump and 0.5 kW for the house fan.

One can question whether it is justified to use the winter residential class peak in the calculations for a summer peaking utility. Some advocates of marginal cost pricing claim that only the contributions to the system peak (which, for a summer peaking utility like PECo, occurs in the summer) should be considered in determining demand related costs. The authors of this report decided to go along with PECo's cost allocation method.

Customer related costs represent the costs of metering, billing, processing payments, etc. Since these costs are incurred for all customers of an electric utility, even for those who may require lights only, they have not been included in the space conditioning cost analysis shown here.

Energy related costs are essentially fuel costs. While PECo uses a constant fuel cost estimated to be 3.21¢/kWh on the average for 1985, it was felt that the lower cost of generating off-peak energy from nuclear and coal plants compared to the on-peak energy which includes oil-steam and gas turbine plants should be considered. A differential of 0.5¢/kWh has therefore been used between off-peak and on-peak energy costs in 1985. This is conservative and close to the value used for internal studies of energy storage previously undertaken by PECo. For many, if not most, utilities in the United States, this differential is considerably larger.

Assuming that 25% of the utility's energy is generated during the eight off-peak hours 11 pm to 7 am, (12 midnight to 8 am during the cooling season), the off-peak and on-peak energy related costs were determined to be 2.835 and 3.335 ¢/kWh, respectively in 1985. The heating systems without off-peak storage were assumed to use 60% of their electrical heating energy during off-peak (nighttime) hours.

Information obtained from measured data subsequent to the conclusion of this project phase showed that only 35% of the heating energy and 22% of the cooling energy is consumed during the off-peak period in systems without off-peak storage. The above cost figures should therefore be adjusted slightly with corresponding modifications in Tables 6-1 through 6-4.

The utility's cost to serve customers using different space conditioning systems were determined on the basis of these cost assumptions. They are shown for the year 1985 in Table 6-1 for heating systems and in Table 6-2 for cooling systems. Corresponding data for 1995 are presented in Tables 6-3 and 6-4.

6.2 OWNING AND OPERATING COSTS

The annual heating costs incurred by a homeowner are made up of the costs the utility charges to serve him and the costs of ownership of the heating equipment in the home. Installed costs were determined for the systems analyzed using manufacturer and contractor data escalated to 1980. Details are given in Appendix D. Equipment cost data for 1980 were used to determine 1985 costs. Equipment cost data for 1990 were used to determine 1995 costs. Equipment costs were escalated at an annual rate of 5 percent from 1980 to 1990.* Annual costs were calculated assuming that these costs are repaid by the homeowner over 20 years at an annual interest rate of 12% on the unpaid balance. This results in a capital recovery factor of 13.4%. These annual costs are shown in the lower portions of Tables 6-1 through 6-4 for conventional and solar assisted heating/cooling systems with and without off-peak storage. All the homes are equipped with central air conditioning which is consistent with the current construction practice in that region.

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*Total installed costs are shown in the fifth line of Tables 6-1 through 6-4.

Table 6-1. Annual Costs for Solar Heating and Heat Pump Systems in Philadelphia, PA (1985)

Consumption, Demand and Cost Data	Resistance Heating (Base System)	Conventional Solar Heat	Solar Heating with Off-Peak Storage (2 Tanks)	Conventional Air-to-Air Heat Pump	Solar Assisted Dual Source Heat Pump w/Direct Heatir from Solar
Annual Consumption, kWh	19,428	12,308	14,508	9,158	7238
Demand at Winter Class Peak, kW	9.16	9.16	0.63	7.19	7.19
Individual Customer Max. Demand,kW	10.50	10.50	36.00	10.50	10.50
Contribution to System Peak, kW	1.61	1.61	1.61	1.61	1.61
1980, Installed Cost, $	1,930	17,237	21,406	2,422	20,818
Demand Related Costs:					
Demand at Class Peak, $32.37/kW	296.51	296.51	20.39	232.74	232.74
Individual Cust.Max. Dmd.,$1.48/kW	15.54	15.54	53.28	15.54	15.54
Contrib. to Sys. Peak, $170.55/kW	274.59	274.59	274.59	274.59	274.59
Energy Related Costs:					
On-Peak Consumption, 3.335 ¢/kWh	259.17	164.19	41.95	122.17	96.55
Off-Peak Consumption,2.835 ¢/kWh	330.47	209.36	375.64	155.78	123.12
Subtotal Cost-to-Serve, $	1176.28	960.19	765.85	800.82	742.54
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	258.39	2,307.00	2,855.00	324.25	2,787
TOTAL ANNUAL COST, $	1435.	3,267.	3,621.	1125.	3529.

Table 6-2. Annual Costs for Solar Air Conditioning in Philadelphia, PA (1985)

Consumption, Demand and Cost Data	Resistance Heating, Conventional Air Conditioning	Conventional Solar Heating, Solar Air Conditioning	Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Cold Storage (2 Tanks)	Solar Heatin w/Off-Peak Storage, Sol A/C w/Off-Pe Hot Storage (2 Tanks)
Annual Consumption, kWh	19,428	12,824	15,524	15,502
Demand at Winter Class Peak, kW	9.16	9.16	0.63	0.63
Individual Customer Max. Demand, kW	10.50	36.00	36.00	36.00
Contribution to System Peak, kW	1.61	4.93	0.71	0.71
1980 Installed Cost, $	1,930	27,980	35,200	31,908
Demand Related Costs:				
Demand at Class Peak, $32.37/kW	296.51	296.51	20.39	20.39
Individual Cust. Max. Dmd., $1.48/kW	15.54	53.28	53.28	53.28
Contrib. to Sys. Peak, $170.55/kW	274.59	840.81	121.09	121.09
Energy Related Costs:				
On-Peak Consumption, 3.335 ¢/kWh	259.17	171.09	44.69	44.69
Off-Peak Consumption,2.835 ¢/kWh	330.47	218.12	402.12	401.49
Subtotal Cost-to-Serve, $	1176.28	1579.81	641.57	640.94
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	258.39	3745.00	4712.00	4271.00
TOTAL ANNUAL COST, $	1435.	5325.	5354.	4912.

Table 6-3. Annual Costs for Solar Space Heating and Heat Pump Systems in Philadelphia (1995)

Consumption, Demand and Cost Data	Resistance Heating (Base System)	Conventional Solar Heating	Solar Heating with Off-Peak Storage (2 Tanks)	Conventional Air-to-Air Heat Pump	Solar Assisted Dual Source Heat Pump w/Direct Heating from Solar
Annual Consumption, kWh	19,428	12,308	14,508	9,158	7238
Demand at Winter Class Peak, kW	9.16	9.16	0.63	7.19	7.19
Individual Customer Max. Demand, kW	10.50	10.50	36.00	10.50	10.50
Contribution to System Peak, kW	1.61	1.61	1.61	1.61	1.61
1990 Installed Cost, $	3,146	28,096	34,892	3,948	33,933
Demand Related Costs:					
Demand at Class Peak, $68.89/kW	630.85	630.85	43.39	495.18	495.18
Individual Cust.Max. Dmd.,$3.19/kW	33.50	33.50	114.84	33.50	33.50
Contrib. to Sys. Peak, $368.06/kW	592.58	592.58	592.58	592.58	592.58
Energy Related Costs:					
On-Peak Consumption, 5.10 ¢/kWh	396.39	251.12	64.17	186.85	147.67
Off-Peak Consumption, 4.346 ¢/kWh	506.57	320.95	575.85	238.81	188.75
Subtotal Cost-to-Serve, $	2159.88	1828.99	1390.82	1546.92	1457.68
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	422.82	3776.10	4689.48	503.59	4560.64
TOTAL ANNUAL COST, $	2583.	5605.	6080.	2051.	6018.

Table 6-4. Annual Costs for Solar Air Conditioning in Philadelphia (1995)

Consumption, Demand and Cost Data	Resistance Heating, Conventional Air Conditioning	Conventional Solar Heating, Solar Air Conditioning	Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Cold Storage (2 Tanks)	Solar Heating w/Off-Peak Storage, Solar A/C w/Off-Peak Hot Storage (2 Tanks)
Annual Consumption, kWh	19,428	12,824	15,524	15,502
Demand at Winter Class Peak, kW	9.16	9.16	0.63	0.63
Individual Customer Max. Demand, kW	10.50	36.00	36.00	36.00
Contribution to System Peak, kW	1.61	4.93	0.71	0.71
1990 Installed Cost, $	3,146	45,607	57,376	51,975
Demand Related Costs:				
Demand at Class Peak, $69.87/kW	640.01	640.01	44.02	44.02
Individual Cust.Max.Dmd., $3.19/kW	33.50	114.84	114.84	114.84
Contrib. to Sys. Peak, $368.08/kW	592.61	1814.63	261.34	261.34
Energy Related Costs:				
On-Peak Consumption, 5.10 ¢/kWh	396.39	261.68	68.35	68.35
Off-Peak Consumption, 4.346 ¢/kWh	506.57	338.38	616.44	635.04
Subtotal Cost-to-Serve, $	2169.07	3169.54	1104.98	1123.58
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	422.82	6129.58	7711.33	6985.44
TOTAL ANNUAL COST, $	2592.	9299.	8816.	8109.

6.3 DISCUSSION OF RESULTS

The additional off-peak thermal storage to electric resistance and solar assisted heating systems reduces their electrical on-peak demands to nominal values (for fan and pump power only); however, their total annual energy consumption is increased by 16 to 27 percent. For the Philadelphia Electric Company it was found that the cost to serve customers with systems incorporating thermal storage is lower than the cost to serve conventional resistance or solar heating customers.

PECo is a utility which is probably as unfavorable to solar heating and off-peak storage as any. It has had a no-growth or slow-growth pattern for the past few years, thus it has relatively low embedded generation costs which result in low demand charges. It is a summer peaking utility, hence solar heating does not affect its peak (summer) demand. The utility has a large pumped storage facility at Muddy Run on the Susquehanna River and it, therefore, derives benefits from off-peak storage within its own network, minimizing the benefits from storage on the part of its customers. Because the utility rarely uses its combustion turbines to satisfy peak demands, its off-peak generation cost differential is very small (calculated to be 0.5 ¢/kWh in 1985). In spite of all these adverse conditions, Tables 6-1 and 6-3 show that PECo's cost to serve off-peak storage customers is lower than the cost to serve conventional resistance and solar heating customers. This demonstrates the beneficial effects of thermal storage. For example, the cost to serve a solar heating customer with off-peak thermal storage is 20% lower in 1985 than the cost to serve a conventional solar heating customer. This cost differential increases to 24% in 1995. The cost to serve a conventional heat pump customer lies somewhere between these two values.

The solar assisted dual source heat pump system has the lowest cost-to-serve in 1985. By 1995, however, this system is slightly more expensive to serve than the solar heating system with off-peak storage.

The results change if the homeowner's cost of installing the storage device is included. Looking at total costs incurred by the utility plus the homeowner, the conventional heat pump is a winner followed by electric resistance heating. All solar systems are more expensive in Philadelphia than conventional systems if they are amortized over 20 years at 12%.

On account of PECo's small off-peak cost differential, the total cost of solar systems incorporating thermal off-peak storage is higher than that of conventional solar systems. The cost of solar assisted heat pumps is higher than the cost of solar heating systems with resistance heating backup. Adding off-peak storage to the former produces only a marginal improvement over a conventional heat pump with off-peak storage (see Section 4.2.7) but greatly increases the first cost. That system was, therefore not analyzed in detail.

In 1985, the cost to serve combined solar heating and solar air conditioning systems is 34% higher than the cost to serve conventional air conditioning systems; in 1995, it is higher by 46%. When either hot or cold off-peak storage is added to the solar air conditioner, its cost to serve is reduced by 52% in 1985, and by 48% in 1995, respectively. The reason is the fact that the off-peak storage prevents the system from adding to the PECo peak system load during hot summer days.

The results change drastically when the homeowner's cost of installing the solar air conditioning system is included. The annual owning cost for solar heating and air conditioning is in the vicinity of $4000 depending on the type of off-peak storage used, while the owning cost for a conventional heating/cooling system is $258 in 1985. The discrepancy is somewhat smaller in 1995, but not significantly so. The solar air conditioning systems total costs are between 3.4 and 3.7 times the costs of conventional air conditioning. In 1985, hot storage costs 8% less and cold storage costs 1% more than no off-peak storage. In 1995, however, these figures change to 13% less and 5% less, respectively, showing that the benefits from thermal storage increase with time. These results also agree with those of other investigators (Ref. 6-1) which found that cold storage is less beneficial than hot storage for solar air conditioning. They also show that solar air conditioning is not likely to achieve any noticeable market penetration in Philadelphia for the remainder of this century.

No tax advantages accruing to the homeowner are included in this analysis since the purpose of this study is to compare national policy alternatives based on least cost. If a tax benefit is given to the solar homeowner, a portion of his cost is distributed to all the other taxpayers of the state or the country. It is shown in Section 5.3 that this may, indeed, be justified on a marginal cost basis but not on the basis of average cost which is used in this section and in Sections 7 through 9 of this report.

7. ENERGY/COST PERFORMANCE FOR DAYTONA BEACH, FLORIDA

7.1 TYPICAL HOME

The typical home chosen for this study is a well insulated 148 m^2 (1600 ft^2) four bedroom home located in Daytona Beach, Florida. A complete description of this home is given in Appendix A. The house is insulated to comply with the Thermal Performance Guidelines for One- and Two-Family Dwellings (Ref. 7-1) assuming an energy cost of 3.5 ¢/kWh. Average annual climatic data used are 900 heating degree days and 2150 cooling hours. Based on the Guidelines, the house is insulated to a value of R-19 in the ceiling, R-12 in the walls, has single-glazed windows and an uninsulated concrete slab floor. Due to the limitations of the TRNSYS (Ref. 7-2) heating load model, a value of R-22 was used for the ceiling insulation. Overall heat loss coefficient of the house is 0.32 kW/°C (605 Btu/hr°F).

7.2 BASIC DATA

7.2.1 Weather Data

The basic analysis was performed for a home in the Daytona Beach, Florida area. While Daytona Beach is not within the Florida Power Corporation's Service Territory, it is the closest city for which adequate weather data is available. Weather data recorded at the Daytona Beach Municipal Airport were used in this analysis.

A typical year was chosen after comparing monthly and annual heating degree days for the years 1952-1964 for Daytona Beach with average monthly and annual values. Data for specific years were obtained from Climatological Data - National Summary, (Ref. 7-3), and average data were taken from the Climatic Atlas of the United States (Ref. 7-4). The monthly and annual values for the year 1964 were found to correspond most closely to the average.

7.2.2 Heating Season

The space heating season in Daytona Beach is defined by the Florida Power Corporation (FPC) to last from November 1 through March 15, with the remainder of year defined as the cooling season. For this reason, the performance of various heating systems were simulated for January 1 - March 15 and November 1 - December 31 of the 1964 calendar year. During the heating season the off-peak period is 11 pm to 7 am and 12 midnight to 8 am during the cooling season as defined by FPC.

7.3 ENERGY ANALYSIS OF SPACE HEATING SYSTEMS (For details, see Appendix B)

7.3.1 Conventional Resistance Space Heating - Base System

The base system is an electrical resistance duct heater. Conversion and transfer of the electrical energy to thermal energy in the resistance coil and to the air stream is assumed to be 100% efficient. Therefore, the electrical energy consumption of this system is equal to the heating load of the house. The annual energy consumption of this system is 8.42 GJ (2346 kWh). Of this total 3.4 GJ (940 kWh) occurred during the on-peak period (7am - 11pm) and 5.0 GJ (1406 kWh) occurs during the off-peak period. Table 7-1 lists the monthly electrical consumption of this system during the on- and off-peak periods. An hourly profile of the power usage of this system by month and the peak usage during each month is given in Table 7-2.

7.3.2 Resistance Space Heating with Off-Peak Storage

A 1.3 m^3 (350 gal) insulated water tank with a 22.7 kW (77,500 Btu/hr) resistance heating coil is used to provide off-peak energy storage. During the off-peak period the tank is heated to set temperatures based on the 12 pm temperature as described in Section 3. With insulation, the heat loss coefficient of the tank is 0.417 W/(m^2°C), (0.73 Btu/hr ft^2°F or R-13.6).

During the peak period, the hot water from the tank is circulated through a heat exchange coil in the air duct where it heats the air being

Table 7-1. Energy Consumed for Resistance Space Heating (kWh)
Daytona Beach, Florida

Month	On-Peak	Off-Peak	Total
January	406	544	950
February	294	447	741
March (1-15)	48	111	159
November	22	42	64
December	170	262	432
Annual Total	940	1406	2346

delivered to the load. Figure 4-2 shows a schematic representation of this system. Circulation of the hot water from the off-peak storage tank through the coil in the hot air duct is provided by a 0.95 litres/second (7 gpm) pump driven by a 60 watt electrical motor. The energy consumption of this pump during peak hours is determined by multiplying this power rating by the fraction of time that the pump is operating.

Simulation Results

The yearly energy consumption of this system is 10.9 GJ (3,040 kWh), an increase of 2.5 GJ (694 kWh) over the yearly energy consumption of the conventional resistance heating system. This 30% increase is due to

- stand-by heat loss from the off-peak storage tank and
- energy required to pump the stored hot water through the coil.

Ninety-three and one-half percent (2840 kWh) of the total energy consumption occurs during the off-peak period. Only six and one-half percent (200 kWh) of the total consumption occurs during the peak period. The monthly electrical consumption of this system during on- and off-peak periods is listed in Table 7-3, and average hourly consumption by month in Table 7-4.

Table 7-2. Average Hourly Profile for Resistance Space Heating in Daytona Beach, Florida

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: DAYTONA BEACH FLORIDA

ALL VALUES = KWH

RESISTANCE HEATING SYSTEM

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1.933	1.597	0.229	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.062	0.840
2	2.056	1.678	0.310	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.105	0.950
3	2.124	1.831	0.400	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.150	1.024
4	2.255	2.081	0.523	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.204	1.073
5	2.376	2.282	0.610	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.217	1.153
6	2.446	2.401	0.647	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.257	1.241
7	2.503	2.496	0.685	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.347	1.379
8	2.390	2.265	0.567	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.413	1.435
9	1.923	1.618	0.297	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.271	1.102
10	1.236	0.997	0.110	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.075	0.602
11	0.719	0.578	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.022	0.265
12	0.441	0.323	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.104
13	0.283	0.188	0.025	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.044
14	0.207	0.122	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.023
15	0.187	0.103	0.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.025
16	0.188	0.104	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.026
17	0.248	0.125	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.033
18	0.367	0.178	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.064
19	0.529	0.326	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.124
20	0.730	0.553	0.045	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.258
21	0.987	0.822	0.101	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.403
22	1.249	1.081	0.139	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.490
23	1.514	1.269	0.164	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.582
24	1.761	1.451	0.179	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.707
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	6.408	4.956	4.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.364	4.747
DAY	14	24	1	1	1	1	1	1	1	1	28	2
HOUR	7	7	7	7	7	7	7	7	7	7	5	7

Table 7-3. Energy Consumed for Resistance Space Heating With Off-Peak Storage (kWh) Daytona Beach, Florida

Month	On-Peak	Off-Peak	Total
January	71	1059	1130
February	64	812	876
March	17	220	237
November	12	227	239
December	36	522	558
Annual Total	200	2840	3040

7.3.3 Conventional Solar Space Heating System

The major components of this system are as shown in Figure 4-4. The components used in this model were chosen to represent the most commonly used components in solar space heating systems today. Nine and seven/tenths square meters (104 ft^2) of flat plate solar collectors with two glass covers and a flat black absorber coating are used in this model. The collectors face due south and are tilted at an angle of 40° (latitude + 11°) from the horizontal. Water from an insulated storage tank is circulated through the collectors by a pump controlled by a differential thermostat. The 35-watt (1/25 hp) pump circulates the water at a mass flow rate of 0.13 ℓ/s (2.1 gpm). This corresponds to a flow rate through the collectors of 50 kg/(m^2h), (1.22 gal/hr ft^2).

The differential thermostat turns the pump on whenever the temperature of the collectors is 5°C (9°F) above the temperature of storage. The pump turns off when the temperature of the collectors is less than 1°C (1.8°F) above the storage temperature.

Thermal energy storage (TES) is provided by a 0.18 m^3 (206 gal) insulated water storage tank. This corresponds to a storage size of 81 kg/m^2 of collector area (2 gal/ft^2). Hot water from the storage

Table 7-4. Average Hourly Profile for Off-Peak Resistance Space Heating in Daytona Beach, Florida

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: DAYTONA BEACH FLORIDA

ALL VALUES = KWH

OFF-PEAK RESISTANCE HEATING SYSTEM

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.042	0.036	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.019
2	1.400	1.617	0.498	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.789	0.935
3	9.927	10.572	2.989	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.866	6.240
4	7.470	5.696	1.177	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.338	4.297
5	5.473	3.483	0.485	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.646	1.614
6	3.593	2.386	0.548	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.208	1.153
7	3.065	2.378	0.612	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.288	1.194
8	2.850	2.532	0.678	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.376	1.245
9	2.234	2.232	0.575	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.406	1.136
10	0.049	0.048	0.015	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.037
11	0.048	0.045	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.031
12	0.038	0.037	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.018
13	0.026	0.026	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.011
14	0.020	0.016	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007
15	0.015	0.008	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
16	0.011	0.008	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
17	0.011	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002
18	0.013	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
19	0.013	0.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004
20	0.018	0.016	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007
21	0.026	0.022	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011
22	0.032	0.029	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.011
23	0.034	0.031	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.013
24	0.038	0.034	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.015
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	22.781	22.781	22.781	0.000	0.000	0.000	0.000	0.000	0.000	0.000	22.722	22.781
DAY	2	9	2	2	2	2	2	2	2	2	1	2
HOUR	3	3	3	3	3	3	3	3	3	3	3	3

tank is circulated through a coil located in the air duct of the house to meet the heating load. A 60-watt (1/12 hp) pump circulates this hot water flow rate of 0.45 ℓ/s (7 gpm).

An electrical resistance coil, located downstream of the hot water coil in the air duct, provides auxiliary energy to the house whenever the solar system cannot meet the heating load.

Simulation Results

Of the 8.4 GJ (8.0 x 10^6 Btu) space heating requirement of the house, 46 percent is provided by the solar heating system. The remaining 4.5 GJ (4.3 x 10^6 Btu) is met by auxiliary electrical power. In addition, 0.12 GJ (33 kWh or 0.11 x 10^6 Btu) of electrical power is consumed in operating the two circulation pumps. The total electrical power consumption of this system is therefore 4.62 GJ (1283 kWh).

Monthly electrical energy consumption of this system during an on- and off-peak periods along with the solar system performance is shown in Table 7.5. The solar system efficiency is defined as the amount of solar derived energy delivered to the load divided by the total solar energy incident on the collectors. Table 7-6 lists the average hourly energy consumption of this system by month along with the peak usage for each month.

The collector efficiency determined by the simulation is 14%. This is due to use of the solar system for space heating only. During the late fall and early spring when there is little or no heating load, the storage tank temperature remains high, thus reducing the efficiency of the solar collectors drastically.

7.4 DOMESTIC WATER HEATING SYSTEMS

7.4.1 Hot Water Load

The hot water heating load is determined for a Daytona Beach family of four with each member using 57 ℓ (15 gal) per day for a total per day usage of 227 ℓ/day (60 gal/day). The hot water supply temperature is set at

Table 7-5. Performance of Conventional Solar Heating System
Daytona Beach, Florida

Month	Auxiliary Energy Consumption On-Peak (kWh)	Off-Peak (kWh)	Total (kWh)	Solar[1/] Fraction (%)	Solar System[2/] Efficiency (%)
January	238	439	677	43	28
February	148	259	407	48	30
March	2	2	4	100	6
November	5	2	7	100	5
December	66	122	188	60	24
Annual Total	459	824	1283	46.3	14.4

1/ Solar Fraction $= \dfrac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$

2/ Solar System Efficiency $= \dfrac{\text{Solar Energy Delivered to Load}}{\text{Total Incident Energy on the Collectors}}$

60°C (140°F) with the inlet water temperature from the city mains being 26.7°C (80°F). A daily hot water flow rate profile based on measured data (Ref. 7-5) is used. Total energy requirements to supply hot water for this family is 11.6 GJ (11 x 10^6 Btu of 3214 kWh) annually.

7.4.2 Conventional Resistance Water Heating-Base System

The base system for domestic water heating in this study is an electric resistance water heater. Conversion and transfer of electrical energy in the hot water storage tank is assumed to be 100% efficient. Heat loss through the walls of the hot water storage tank are the only energy losses present in this system.

Table 7-[illegible] Average Hourly Profile for Conventional Solar Space Heating System in Daytona Beach, Florida

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: DAYTONA BEACH FLORIDA

ALL VALUES = KWH

CONVENTIONAL SOLAR HEATING SYSTEM

SOLAR COLLECTOR AREA = 104 FT**2

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1.328	0.638	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.347
2	1.564	0.926	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.425
3	1.741	1.092	0.058	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.468
4	1.880	1.292	0.114	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.568
5	2.045	1.467	0.122	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.599
6	2.098	1.568	0.189	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.615
7	2.206	1.751	0.256	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.640
8	2.143	1.639	0.228	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.690
9	1.649	1.119	0.099	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.019	0.605
10	0.729	0.489	0.026	0.002	0.004	0.002	0.004	0.004	0.004	0.002	0.014	0.264
11	0.309	0.291	0.028	0.020	0.022	0.021	0.019	0.021	0.019	0.017	0.025	0.055
12	0.174	0.167	0.027	0.028	0.027	0.026	0.025	0.025	0.023	0.022	0.028	0.037
13	0.109	0.157	0.025	0.030	0.029	0.027	0.022	0.023	0.025	0.022	0.027	0.036
14	0.083	0.089	0.026	0.028	0.028	0.025	0.021	0.020	0.022	0.019	0.023	0.031
15	0.077	0.098	0.024	0.021	0.025	0.021	0.020	0.017	0.018	0.013	0.015	0.028
16	0.068	0.104	0.013	0.003	0.006	0.005	0.007	0.004	0.003	0.001	0.002	0.016
17	0.111	0.090	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.020
18	0.187	0.098	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042
19	0.238	0.129	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.058
20	0.277	0.195	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.068
21	0.327	0.244	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072
22	0.538	0.274	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.080
23	0.819	0.296	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.112
24	1.138	0.332	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.211
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	6.408	4.956	4.208	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.364	4.747
DAY	14	24	1	1	1	1	1	1	1	1	28	2
HOUR	7	7	7	7	7	7	7	7	7	7	5	7

A 0.228 m^3 (60 gal) insulated hot water storage tank with a 8.8 kW (30,000 Btu/hr) resistance heating coil is used to supply the required hot water. The heat loss coefficient of the tank is 0.417 W/(m^2 °C) (0.073 Btu/hrft^2°F or R-13.6).

Since it is assumed that the conditions imposed on this system are constant throughout the year the performance of this system needs to be simulated for a single day only. The daily electrical energy consumption of the system is 34,380 kJ (9.55 kWh). On- and off-peak consumption is given in Table 7-7. To find the monthly values, the daily values should simply be multiplied by the number of days in the month.

Table 7-7. Energy Consumed for Resistance Water Heating (kWh) Daytona Beach, Florida

	On-Peak	Off-Peak	Total
Daily	8.52	1.03	9.55
Annual	3110	376	3486

7.4.3 Off-Peak Resistance Water Heating

A 0.456 m^3 (120 gal) insulated hot water storage tank with a 8.8 kW (30,000 Btu/hr) resistance heating coil is heated to 70°C (158°F) during the daily off-peak period. It is heated 10°C (18°F) above the required supply temperature so that, with storage losses, it will be able to supply 60°C (140°F) water at the end of the on-peak period. A mixing valve is included for scald protection. The tank is insulated to a value of 0.417 W/(m^2 °C) (0.073 Btu/hrft^2 °F or R-13.6).

The daily electrical energy consumption of this system is 36,180 kJ (10.05 kWh) with all of the consumption occurring during the off-peak period. Table 7-8 lists the on- and off-peak electrical consumption.

Table 7-8. Energy Consumed for Off-Peak Resistance Water Heating (kWh) Daytona Beach, Florida

	On-Peak	Off-Peak	Total
Daily	0	10.05	10.05
Annual	0	3669	3669

7.4.4 Conventional Solar Water Heating

The major components of this system are shown schematically in Figure 7-1. The components used in this model are chosen to represent those commonly used in solar hot water heating systems today. The solar system was preliminarily sized to meet 50 percent of the hot water load. Three point eight eight square meters (41.8 ft^2) of flat plate solar collectors with two glass covers and a flat black absorber coating are used. The collectors face due south and are tilted at an angle of 30° (latitude +1°) from the horizontal. Water from an insulated storage tank is circulated through the collectors by a pump controlled by a differential thermostat. A 12.5-watt (1/60 hp) pump circulates the water at a mass flow rate through the collectors of 50 $kg/(m^2h)$, (1.22 $gal/hrft^2$).

The differential thermostat turns the pumps on whenever the temperature of the collectors is 5°C (9°F) above the temperature of the solar storage tank. The pump turns off when the temperature of the collectors is less than 1°C (1.8°F) above the solar storage temperature.

Thermal energy storage for the solar collectors is provided by a 0.228 m^3 (60 gal) insulated water storage tank. Cold water from the supply mains is fed into this tank where it is heated. The water then flows to the bottom of a 0.284 m^3 (75 gal) insulated convential hot water heater.A 8.8 kW (30,000 Btu/hr) resistance heating coil maintains the conventional heater water temperature at 60°C (140°F). Hot water is

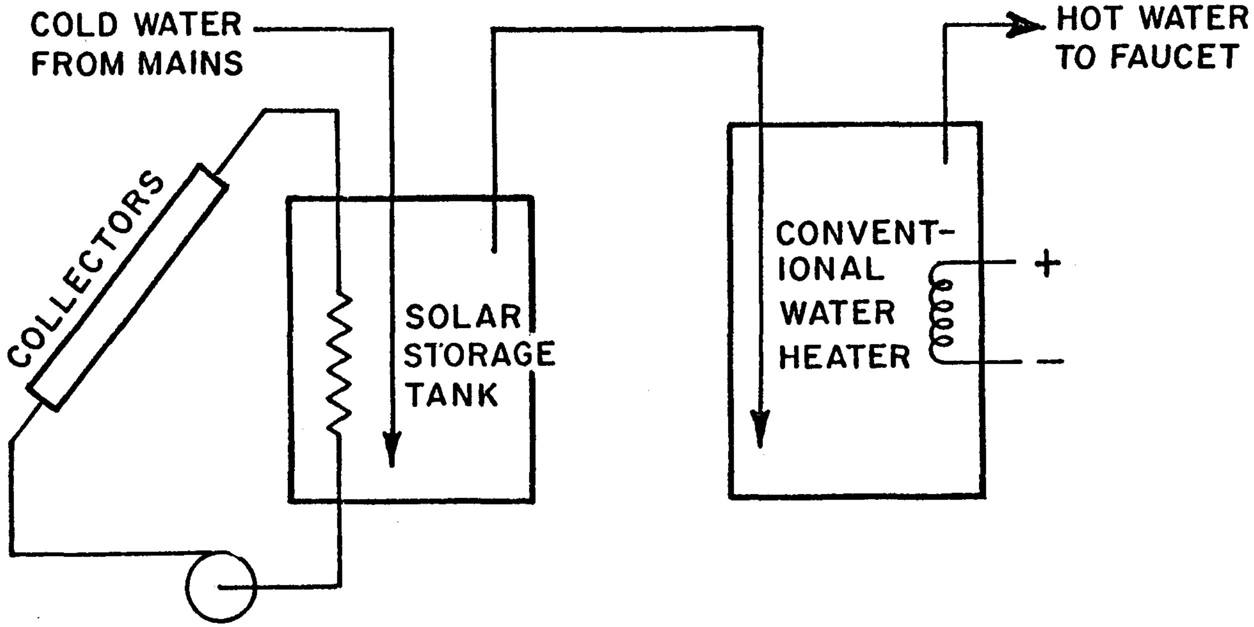

Figure 7-1. Conventional Solar Water Heating System

supplied to the house from the auxiliary water tank as required. To prevent scalding, a mixing valve set at 60°C (140°F) is located between the auxiliary tank and the house faucets.

Simulation Results

Fifty-four percent of the 11.6 GJ (11 x 10^6 Btu) annual load is supplied by the solar system. Of the total annual electrical consumption (1489 kWh), eighty-three percent (1420 kWh) occurs during the on-peak periods. Monthly electrical energy consumption during on- and off-peak periods along with monthly solar system performance is presented in Table 7-9. Average hourly consumption of this system along with the peak usage for each month is listed in Table 7-10.

Table 7-9. Performance of Conventional Solar Water Heating System in Daytona Beach, Florida

Month	Load (10^6 kJ)	Auxiliary Energy Use (kWh)			S.F* (%)
		On-Peak	Off-Peak	Total	
Jan.	0.984	164	27	191	30.0
Feb.	0.888	123	21	144	41.5
Mar.	0.984	99	21	120	56.3
Apr.	0.952	63	17	80	69.7
May	0.984	70	18	88	67.7
June	0.952	64	17	81	68.3
July	0.984	95	20	115	57.9
Aug.	0.984	95	21	116	57.8
Sept.	0.952	87	19	106	59.6
Oct.	0.984	114	22	136	50.4
Nov.	0.952	119	22	141	46.8
Dec.	0.984	145	24	169	38.0
TOTAL	11.58	1238	249	1487	53.8

$$\text{*S.F. = Solar Fraction} = \frac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$$

Solar Collector Area = 3.88 m^2 (41.7 ft^2)

Solar Storage Volume = .288 m^3 (60 gal)

Table 7-10. Average Hourly Profile for Conventional Solar Water Heating System in Daytona Beach, Florida

WATER HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: DAYTONA BEACH FLORIDA

ALL VALUES = KWH

SOLAR WATER HEATING SYSTEM

SOLAR COLLECTOR AREA = 42 FT**2

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.215	0.218	0.163	0.106	0.130	0.124	0.137	0.149	0.134	0.163	0.160	0.200
2	0.071	0.064	0.061	0.055	0.047	0.065	0.059	0.058	0.052	0.052	0.068	0.058
3	0.063	0.062	0.057	0.057	0.048	0.051	0.050	0.048	0.050	0.049	0.054	0.052
4	0.061	0.059	0.054	0.052	0.048	0.049	0.049	0.048	0.048	0.048	0.050	0.051
5	0.058	0.054	0.054	0.052	0.048	0.048	0.048	0.048	0.048	0.048	0.049	0.051
6	0.057	0.051	0.051	0.050	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.050
7	0.106	0.089	0.079	0.067	0.070	0.070	0.069	0.081	0.080	0.094	0.093	0.101
8	0.188	0.168	0.118	0.099	0.103	0.102	0.107	0.124	0.118	0.160	0.166	0.196
9	0.232	0.226	0.165	0.141	0.147	0.146	0.152	0.171	0.165	0.210	0.210	0.247
10	0.263	0.266	0.210	0.186	0.182	0.179	0.201	0.224	0.222	0.277	0.262	0.283
11	0.245	0.251	0.213	0.178	0.179	0.185	0.225	0.233	0.215	0.281	0.244	0.273
12	0.210	0.194	0.149	0.120	0.117	0.120	0.162	0.159	0.157	0.215	0.167	0.201
13	0.181	0.151	0.118	0.081	0.079	0.080	0.129	0.124	0.120	0.170	0.125	0.157
14	0.204	0.158	0.115	0.068	0.077	0.060	0.119	0.117	0.109	0.156	0.128	0.162
15	0.164	0.141	0.093	0.048	0.055	0.048	0.090	0.089	0.077	0.118	0.109	0.120
16	0.152	0.126	0.076	0.038	0.046	0.039	0.072	0.072	0.066	0.092	0.099	0.118
17	0.140	0.108	0.064	0.034	0.040	0.036	0.065	0.065	0.058	0.080	0.090	0.110
18	0.154	0.117	0.058	0.022	0.031	0.035	0.060	0.066	0.052	0.080	0.094	0.123
19	0.196	0.152	0.079	0.030	0.038	0.039	0.075	0.079	0.070	0.104	0.124	0.161
20	0.297	0.238	0.138	0.060	0.068	0.072	0.123	0.137	0.122	0.183	0.216	0.248
21	0.371	0.296	0.210	0.109	0.122	0.105	0.190	0.219	0.198	0.280	0.290	0.360
22	0.366	0.295	0.226	0.131	0.136	0.121	0.208	0.224	0.212	0.270	0.282	0.343
23	0.350	0.297	0.221	0.141	0.155	0.133	0.212	0.218	0.214	0.253	0.272	0.306
24	0.337	0.288	0.216	0.148	0.161	0.162	0.213	0.208	0.208	0.239	0.251	0.291
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	0.747	0.703	0.492	0.419	0.521	0.442	0.530	0.527	0.584	0.657	0.653	0.628
DAY	18	4	29	26	2	27	28	20	13	15	24	15

7.4.5 Solar Water Heating with Off-Peak Storage

This system is identical to the conventional solar water heating system except that during the off-peak period the auxiliary water storage is heated to 70°C (158°F). The resistance heating coil in the auxiliary tank is inoperable during the on-peak period.

Simulation Results

The solar system provides 52.3 percent of the hot water load. However, only 2% (33 kWh) of the total electrical energy consumption (1534 kWh) occurs during the on-peak period. Table 7-11 lists the monthly on- and off-peak electrical energy consumption as well as the monthly solar system performance. The average hourly profile by month for this system is presented in Table 7-12.

Table 7-11. Performance of Solar Water Heating System With Off-Peak Storage in Daytona Beach, Florida

Month	Load (10^6 kJ)	Auxiliary Energy Use (kWh)			S.F*
		On-Peak	Off-Peak	Total	(%)
Jan.	0.984	2	185	187	31.6
Feb.	0.888	2	142	144	41.7
Mar.	0.984	3	121	124	54.6
Apr.	0.952	3	87	90	65.8
May	0.984	3	95	98	64.1
June	0.952	3	89	92	65.3
July	0.984	3	117	120	56.0
Aug.	0.984	3	118	121	55.7
Sept.	0.952	3	110	113	57.3
Oct.	0.984	3	134	137	49.9
Nov.	0.952	3	138	141	46.6
Dec.	0.984	2	164	166	39.0
TOTAL	11.6	33	1500	1533	52.3

$$\text{*S.F.} = \text{Solar Fraction} = \frac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$$

Solar Collector Area = 3.88 m^2 (41.7 ft^2)

Solar Storage Tank = .228 m^3 (60 gal)

Off-Peak Storage Tank = .303 m^3 (80 gal)

Table 7-12. Average Hourly Profile for Solar Water Heating System with Off-Peak Storage in Daytona Beach, Florida

WATER HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: DAYTONA BEACH FLORIDA

ALL VALUES = KWH

SOLAR WATER HEATING SYSTEM WITH OFF-PEAK STORAGE

SOLAR COLLECTOR AREA = 42 FT**2

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.720	0.616	0.447	0.287	0.334	0.296	0.413	0.434	0.406	0.491	0.556	0.659
2	0.093	0.083	0.107	0.072	0.063	0.086	0.098	0.080	0.076	0.073	0.104	0.080
3	0.065	0.063	0.079	0.057	0.059	0.066	0.065	0.062	0.065	0.062	0.066	0.068
4	0.064	0.059	0.075	0.058	0.060	0.064	0.061	0.058	0.062	0.060	0.060	0.069
5	0.061	0.059	0.068	0.057	0.059	0.062	0.058	0.058	0.060	0.059	0.060	0.069
6	0.061	0.063	0.064	0.059	0.058	0.059	0.058	0.058	0.058	0.059	0.058	0.069
7	0.108	0.100	0.088	0.076	0.077	0.074	0.076	0.084	0.085	0.092	0.086	0.097
8	0.347	0.285	0.221	0.128	0.144	0.165	0.227	0.216	0.195	0.233	0.271	0.323
9	0.000	0.002	0.003	0.001	0.002	0.002	0.003	0.004	0.002	0.002	0.001	0.000
10	0.006	0.008	0.010	0.012	0.012	0.012	0.012	0.012	0.011	0.010	0.009	0.008
11	0.009	0.010	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.011	0.011	0.010
12	0.011	0.011	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
13	0.012	0.011	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
14	0.012	0.011	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
15	0.011	0.010	0.012	0.012	0.012	0.012	0.012	0.011	0.012	0.012	0.012	0.012
16	0.008	0.009	0.012	0.012	0.012	0.012	0.011	0.009	0.012	0.011	0.010	0.010
17	0.002	0.004	0.010	0.010	0.012	0.010	0.010	0.008	0.009	0.006	0.005	0.001
18	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
21	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
23	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
24	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	0.962	0.916	0.863	0.818	0.834	0.729	0.843	0.821	0.887	0.887	0.946	0.945
DAY	19	6	30	30	4	28	28	30	12	16	24	24
HOUR	1	1	1	1	1	1	1	1	1	1	1	1

7.5 ENERGY ANALYSIS OF SPACE COOLING SYSTEMS

The performance of two solar air conditioning systems was compared with that of a conventional vapor compression air conditioner. Cooling loads were calculated for the typical house described in Subsection 7.1 using weather data from 1964 for Daytona Beach, Florida. Two types of solar air conditioning systems were considered (refer to Figures 4-24 and 4-26). The solar A/C are 31,640 kJ/hr (2.5 ton) lithium-bromide absorption chillers. The cooling tower which would be required is not shown. The conventional solar A/C operates with hot water from the solar storage tank whenever possible. When solar heat is not available, valve V-1 bypasses the solar storage, and the auxiliary heater supplies energy to the air conditioner. The solar A/C with off-peak hot water storage also uses solar energy whenever possible. However, when solar storage is depleted, heat is obtained from the off-peak storage tank. The auxiliary heater in the off-peak storage tank only operates between 12 midnight and 8 AM. The off-peak storage tank is sized so that all cooling loads during the day can be met with heat from the off-peak storage tank. Consequently, the only electricity usage by this system during the day is by pumps and fans. These systems are discussed further in Appendix B.

The solar air conditioning systems were simulated with 55.8 m^2 (600 ft^2) of collector area and a solar storage size equivalent to 81.5 kg/m^2 (2 gal/ft^2) of collector area. The off-peak storage tank had a capacity of 3.5 m^3.

Since the collector area for the solar air conditioning system was so much larger, 55.8 m^2 (600 ft^2) compared to 9.68 m^2 (104 ft^2), than that used for the solar space heating systems, it was necessary to simulate the performance of a solar space heating system using this larger collector area. The simulation results for the solar space heating and cooling systems, both with 55.8 m^2 (600 ft^2) of collectors, were then combined to provide the annual performance of a system using such a large collector area.

Simulation Results

Solar space heating utilizing 55.8 m^2 (600 ft^2) provides 100% of the space heating requirement in Daytona Beach. Therefore the only energy use during the heating season is by the pumps used to circulate fluid through the collectors and to deliver hot fluid from the storage tank to the load.

Monthly electric energy usage for each system is shown in Table 7-13. The on-peak period runs from 8AM to 12 midnight, the off-peak period from 12 midnight to 8 AM. It can be seen that the solar systems use nearly three times as much electrical energy during the cooling season as does the conventional (compression) air conditioner. However, the solar A/C with off-peak storage reduces on-peak energy consumption.

Table 7-13. Air Conditioning Energy Consumption (kWh)

	Compression A/C		Conventional Solar A/C		Solar A/C With Off-Peak Storage	
	On Peak	Off Peak	On Peak	Off Peak	On Peak	Off Peak
March	188	7	280	41	157	313
April	409	21	612	131	239	587
May	604	54	904	303	282	1067
June	858	134	1930	679	270	2319
July	834	172	2299	882	279	2997
August	811	174	2273	891	274	2961
September	682	130	1886	698	269	2414
October	336	37	1002	229	226	1159
Subtotals	4722	729	11,186	3854	1996	13,817
Totals	5451		15,040		15,813	

Peak period: 8AM to 12PM, off-peak period: 12PM to 8AM.

The monthly peak electrical demands for all systems are shown in Table 7-14. The magnitudes of the demands and the day and hour (Eastern Standard Time) when they occur are given. The peaks for the solar systems are much larger than those of the conventional compression system. The peaks for the conventional solar A/C occur when solar storage is depleted and the auxiliary heater is energized. As can be seen in Table 7-14, this usually occurs during the middle of the day. The solar A/C with off-peak storage, however, peaks at night when the auxiliary heater in the off-peak storage tank is on. During the day, the system needs electricity for pumps and fans only. Because there are so many pumps and fans, the day-time demand may approach 0.6 kW.

System average daily demand profiles for each month are shown in Tables 7-16 through 7-18. That is, for a given month and hour, the demand shown is the average for that hour during the month.

Table 7-14. Air Conditioning System Monthly Peak Demands (kW)

	Compression A/C			Conventional Solar A/C			Solar A/C With Off-Peak Storage
Month	Day	Hour	Demand	Day	Hour	Demand	Demand*
March	3	16	2.40	3	17	7.80	5.46
April	8	16	2.43	24	18	7.01	9.84
May	29	15	2.56	12	18	8.04	10.61
June	16	15	3.14	1	16	10.66	14.22
July	13	17	3.15	11	16	10.90	15.36
August	4	17	3.16	10	14	10.70	15.22
September	1	15	2.78	22	14	9.74	15.21
October	9	15	2.08	5	14	8.89	10.39

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*These demands occur between the hours of midnight and 8 AM when the off-peak storage is being heated with electrical energy. When the off-peak storage is not being charged, the maximum demand is 0.69 kW.

The performance of the solar components for each solar air conditioning system are shown in Table 7-15.

Table 7-15. Performance of Solar Air Conditioning System Solar Components

	Conventional Solar A/C		Solar A/C With Off-Peak Hot Storage	
	GJ	Btu x 10^6	GJ	Btu x 10^6
Solar Radiation Incident on the Collectors	260	246	260	246
Energy Collected and Delivered to Storage	46.0	43.6	46.3	43.9
Collector Efficiency	17.7%		17.8%	
Energy Lost from Solar Storage	3.2	3.0		
Solar Storage Efficiency	93.0%			
Auxiliary Energy Input to Off-Peak Storage	-	-	48.1	45.6
Energy Lost from Off-Peak Storage	-	-	3.5	3.3
Off-Peak Storage Efficiency	-		92.7%	

Table 7-16. Average Hourly Energy Consumption for Conventional Air Conditioning in Daytona Beach, Florida

ALL VALUES = KWH

SYSTEM = CONVENTIONAL COMPRESSION AIR CONDITIONER

HOUR	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	0.074	0.198	0.395	0.830	0.930	0.947	0.785	0.256
2	0.050	0.139	0.284	0.663	0.790	0.815	0.651	0.202
3	0.033	0.102	0.205	0.542	0.700	0.732	0.569	0.159
4	0.022	0.068	0.154	0.442	0.626	0.656	0.506	0.137
5	0.014	0.045	0.117	0.361	0.555	0.591	0.459	0.119
6	0.010	0.032	0.088	0.291	0.471	0.520	0.421	0.103
7	0.009	0.040	0.148	0.453	0.574	0.563	0.406	0.096
8	0.027	0.090	0.346	0.874	0.904	0.803	0.525	0.137
9	0.068	0.200	0.614	1.282	1.237	1.106	0.791	0.235
10	0.123	0.375	0.919	1.599	1.498	1.409	1.105	0.379
11	0.226	0.643	1.206	1.874	1.739	1.704	1.416	0.564
12	0.337	0.961	1.425	2.114	1.922	1.931	1.670	0.767
13	0.474	1.233	1.588	2.257	2.021	2.056	1.831	0.981
14	0.620	1.402	1.708	2.313	2.124	2.104	1.937	1.166
15	0.711	1.462	1.761	2.345	2.183	2.097	1.995	1.250
16	0.735	1.445	1.727	2.316	2.162	2.062	1.952	1.211
17	0.740	1.352	1.636	2.206	2.075	1.994	1.807	1.066
18	0.633	1.179	1.517	2.056	1.924	1.845	1.592	0.825
19	0.470	0.951	1.341	1.851	1.721	1.632	1.382	0.555
20	0.285	0.740	1.124	1.618	1.515	1.447	1.245	0.465
21	0.200	0.582	0.962	1.426	1.363	1.325	1.149	0.400
22	0.184	0.449	0.800	1.266	1.238	1.224	1.043	0.349
23	0.148	0.362	0.652	1.118	1.131	1.132	0.964	0.310
24	0.094	0.297	0.522	0.990	1.053	1.065	0.885	0.289

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Table 7-17. Average Hourly Energy Consumption for Conventional Solar Air Conditioning in Daytona Beach, Florida

ALL VALUES = KWH

SYSTEM = CONVENTIONAL SOLAR AIR CONDITIONER

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	0.273	1.035	2.013	3.955	4.648	4.796	4.117	1.496
2	0.226	0.828	1.503	3.327	4.027	4.168	3.478	1.158
3	0.173	0.626	1.110	2.640	3.610	3.815	3.036	1.005
4	0.133	0.411	0.877	2.231	3.333	3.449	2.778	0.830
5	0.118	0.338	0.724	1.912	2.900	3.181	2.527	0.738
6	0.112	0.274	0.592	1.598	2.275	2.588	2.339	0.676
7	0.111	0.306	0.971	2.520	3.084	2.732	2.220	0.630
8	0.162	0.535	1.975	4.443	4.569	4.018	2.788	0.855
9	0.275	0.841	3.040	6.125	5.930	5.367	4.095	1.302
10	0.441	1.254	3.506	7.218	6.844	6.314	5.350	1.925
11	0.592	1.254	1.205	4.624	5.176	4.765	3.611	2.211
12	0.603	1.039	1.029	2.558	2.961	3.449	2.853	2.084
13	0.320	0.971	1.032	1.936	3.161	2.399	2.473	1.754
14	0.408	0.946	0.897	1.614	3.358	2.501	2.482	2.086
15	0.465	1.063	1.148	2.546	3.543	2.997	2.968	1.880
16	0.776	1.128	1.455	3.099	3.688	3.657	3.357	2.401
17	1.047	1.095	1.221	2.976	4.446	5.421	3.319	2.207
18	0.545	1.455	1.638	3.584	4.366	4.800	2.859	2.064
19	0.413	1.518	1.625	3.586	3.236	3.589	4.185	2.380
20	0.875	1.612	1.328	3.772	5.121	5.045	5.489	2.301
21	0.759	1.702	2.423	5.318	5.746	6.113	5.415	2.315
22	0.675	1.671	2.623	5.452	5.815	5.976	5.049	2.009
23	0.473	1.497	2.594	5.249	5.583	5.621	4.759	1.788
24	0.382	1.365	2.431	4.682	5.210	5.323	4.601	1.638

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Table 7-18. Average Hourly Energy Consumption for Solar Air Conditioning with Off-Peak Hot Storage in Daytona Beach, Florida

ALL VALUES = KWH

SYSTEM = SOLAR AIR CONDITIONER WITH OFF PEAK HOT WATER STORAGE

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
2	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
3	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
4	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
5	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
6	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
7	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
8	1.263	2.446	4.304	9.661	12.086	11.940	10.057	4.672
9	0.078	0.210	0.431	0.497	0.486	0.484	0.462	0.228
10	0.168	0.324	0.544	0.568	0.548	0.548	0.536	0.270
11	0.202	0.421	0.551	0.572	0.567	0.562	0.555	0.355
12	0.232	0.504	0.570	0.577	0.566	0.561	0.562	0.399
13	0.290	0.528	0.572	0.574	0.558	0.555	0.562	0.440
14	0.293	0.528	0.574	0.567	0.555	0.548	0.557	0.451
15	0.332	0.517	0.570	0.562	0.554	0.540	0.550	0.446
16	0.313	0.485	0.554	0.547	0.543	0.530	0.523	0.423
17	0.334	0.460	0.486	0.499	0.489	0.481	0.476	0.413
18	0.337	0.459	0.475	0.475	0.475	0.475	0.475	0.442
19	0.336	0.458	0.475	0.475	0.475	0.475	0.475	0.443
20	0.319	0.443	0.475	0.457	0.475	0.464	0.475	0.429
21	0.273	0.443	0.475	0.443	0.475	0.449	0.474	0.428
22	0.230	0.443	0.475	0.434	0.460	0.437	0.459	0.412
23	0.227	0.439	0.475	0.429	0.418	0.414	0.459	0.397
24	1.110	1.309	1.410	1.367	1.343	1.353	1.397	1.314

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7.6 UTILITY COST COMPONENTS

Florida Power Corporation (FPC) generously offered its cooperation in this project without reimbursement. Although Daytona Beach is not within its service territory, its climate is representative of the climate in the shore portions of that territory. Since extensive weather and solar radiation data do not exist for any other location within the FPC terriroty, the data for Daytona Beach were used to determine the effects of solar and off-peak storage utilization on that utility.

Florida Power is a medium-sized utility serving 735,000 customers in a service teritory of 20,000 square miles covering the central and northwestern part of that state inhabited by three million people. Although most of its energy sales occur during the summer, its demand peak (4.2 million kW in 1978/79 compared to a net generating capacity of 4.9 million kWh) occurs in the winter. The utility presently obtains a quarter of its energy from coal but is planning to increase that fraction to more than 50% within five years. Its average fuel cost in 1979 was $2.01 per million Btu or 1.9 ¢/kWh.

Not having detailed FPC data on the diversity of conditioning equipment available, a diversity factor of(1/0.7) for both conventional and solar heating and air conditioning was assumed. Electric water heating is wide-spread throughout the FPC territory. A contribution to systems peak from water heating of 0.2 kW per customer was assumed based on data obtained from other winter peaking utilities.

The installed capacity cost for units coming on line in 1980 was $688/kW. FPC assumes that this cost increases at a rate of 8.7 percent per year. Thus, this cost is $1044/kW for generating capacity coming on line in 1985, and $2404 for 1995. A capital recovery factor of 0.15 was used. The fuel cost escalation from present (1980) values was also assumed to be 8.7 percent per year.

FPC was unable to provide a detailed breakdown of their costs of service similar to that obtained from PECo (see Section 6.3, Tables 6-1 through 6-4). These costs were, therefore estimated by prime contractor personnel with the aid of FPC's latest Residential Rate Schedules (Ref. 7-6) and Ten-Year Statistical Report (Ref. 7-7) using the following procedure.

The ratio of cost to revenue was found by subtracting the net income from the total revenue and dividing the difference by the total revenue. The on-peak and off-peak residential rate schedules (Ref. 7-6) were then multiplied by this ratio to obtain an approximate cost-to-serve. This procedure assumes that the tariff for residential on-peak and off-peak energy is based on proper cost accounting and that, therefore, in the absence of true cost-to-serve information, the recently published tariff would be the best indicator of that cost. The results of this analytical procedure are shown in Table 7-19. As seen in the table, a two-dollar per month additional meter charge is included to cover the cost of the special meter and its reading.

Table 7-19. Florida Power Corporation Cost-to-Serve Data (as determined by a Franklin Research Center procedure)

Item	1980	1985	1995
Capacity Cost for Generation Coming On-Line in Stated Year ($/kW)	688	1044	2404
Capital Recovery Factor	0.15	0.15	0.15
Annual Peak Demand Cost ($/kW)	103.20	156.61	360.68
Energy Cost, Off-Peak (¢/kWh)	2.84	4.31	9.93
Energy Cost, On-Peak (¢/kWh)			
(November - April)	10.68	16.21	37.33
(May - October)	7.00	10.62	24.46
Annual Metering Charge ($)	24.00	36.42	83.88

7.7 DISCUSSION OF RESULTS

The results of the analyses are presented in Tables 7-20 for space and water heating systems and in Table 7-21 for air conditioning systems, both solar and conventional with and without off-peak storage, for the year 1985. Corresponding results for 1995 are given in Tables 7-22 and 7-23, respectively.

Solar Space Heating

Adding off-peak storage to a space heating system which is sufficient to eliminate all on-peak demands except for pumps and fans increases the annual energy consumption by 9% and reduces the cost to serve by almost 50%. Even the total cost (to the utility plus the homeowner) is decreased by 13% in 1985 and by 24% in 1995, demonstrating the increasing benefits of storage in the future. The cost to serve solar space heating systems is 7% lower than the cost to serve a resistance heating system,while the total cost for solar heating is 39% higher in 1985 and 24% higher in 1995 than for resistance heating. Even the addition of off-peak storage does not reduce the cost of solar heating sufficiently to make it economical (see Section 8). Solar space heating, therefore,does not appear to be economical in Daytona Beach through the rest of the century, unless utility costs change drastically.

Solar Water Heating

The advantages of off-peak storage for water heating are even greater than for space heating. The energy penalty is only 5%, but the cost to serve the off-peak systems is 64% lower in 1985 and 55% lower in 1995. Total costs are approximately cut in half. Solar water heating without off-peak storage has a slightly higher cost-to-serve than resistance heating with storage (by 16%) in 1985, but this cost differential reverses in 1995 for a 6% cost advantage of the solar system. Even in 1985 the solar system has a total cost advantage of 6% which increases to 11% by 1995. The addition of off-peak storage to the solar water heating system decreases the cost to serve significantly: by 62% in 1985 and by 43% in 1995. The total cost of that system, however, is approximately 20%

Table 7-20. Annual Costs for Solar Space and Water Heating Systems in Daytona Beach (1985)

Consumption and Cost Data	Resistance Space Heating (Base System)	Resistance Space Heating w/Off-Peak Storage	Conventional Solar Space Heating	Resistance Water Heating (Base System)	Resistance Water Heating w/Off-Peak Storage	Conventional Solar Water Heating	Solar Water Heating w/ Off-Peak Stor
Annual Consumption, kWh	7797	8491	6734	3486	3669	1489	1534
Off-Peak Consumption, kWh	2135	3569	1553	376	3669	249	1501
On-Peak Consumption							
(Heating Season), kWh	1092	362	628	1031	0	531	9
(Cooling Season), kWh	4570	4560	4553	2079	0	709	24
Individual Customer Max. Dmd., kW	6.41	22.8	6.41	0.77	0.485	0.747	0.962
Contribution to System Peak, kW	4.49	0.06	4.49	0.20	0	0.07	0
1980 Installed Cost, $	2269	5528	7523	360	573	2459	2499
Demand Related Costs:							
Contrib. to Sys. Peak, $156.61/kW	703.18	9.40	703.18	31.32	0	10.96	0
Meter Cost, $36.42/yr	0	36.42	0	0	36.42	0	36.42
Energy Related Costs:							
Off-Peak Consumption, 4.31 ¢/kWh	92.02	153.82	66.93	16.21	158.13	10.73	64.69
On-Peak Consumption,							
(Heating Season), 16.21 ¢/kWh	177.01	58.68	101.80	167.13	0	86.08	1.46
(Cooling Season), 10.62 ¢/kWh	485.33	484.27	483.53	220.79	0	75.30	3.89
Subtotal Cost-to-Serve, $	1457.54	742.60	1355.44	435.44	194.55	183.07	106.46
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	245.01	742.96	1011.09	48.38	77.41	330.49	335.87
TOTAL ANNUAL COST, $	1703.	1486.	2367.	484.	272,	514.	442,

Table 7-21. Annual Costs for Solar Air Conditioning for Daytona Beach (1985)

Consumption and Cost Data	Resistance Space Heating, Conventional Air Conditioning	Solar Space Heating, 55.7m^2 Solar Air Conditioning	Solar Space Heating, 55.7m^2 Solar Air Conditioning with Off-Peak Hot Storage
Annual Consumption, kWh	7797	15,231	16,003
Off-Peak Consumption, kWh	2135	3,869	15,058
On-Peak Consumption			
(Heating Season), kWh	1092	372	249
(Cooling Season), kWh	4570	10,990	1,923
Individual Customer Max.Dmd., kW	6.41	10.90	15.36
Contribution to System Peak, kW	4.49	0.06	0.06
1980 Installed Cost, $	2,269	28,908	33,296
Demand Related Costs:			
Contrib. to Sys. Peak, $156.61/kW	703.18	9.40	9.40
Meter Cost, $36.42/yr	0	0	36.42
Energy Related Costs:			
Off-Peak Consumption, 4.31 ¢/kWh	92.02	166.75	649.00
On-Peak Consumption			
(Heating Season), 16.21 ¢/kWh	177.01	60.30	40.36
(Cooling Season), 10.62 ¢/kWh	485.33	1167.14	204.22
Subtotal Cost-to-Serve, $	1457.54	1403.59	939.40
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	245.01	3885.24	4474.98
TOTAL ANNUAL COST, $	1703.	5289.	5414.

Table 7-22. Annual Costs for Solar Space and Water Heating Systems in Daytona Beach (1995)

Consumption and Cost Data	Resistance Space Heating (Base System)	Resistance Space Heating w/Off-Peak Storage	Conventional Solar Space Heating	Resistance Water Heating (Base System)	Resistance Water Heating w/Off-Peak Storage	Conventional Solar Water Heating	Solar Water Heating w Off-Peak Sto
Annual Consumption, kWh	7797	8491	6734	3486	3669	1489	1534
Off-Peak Consumption, kWh	2135	3569	1553	376	3669	249	1501
On-Peak Consumption							
(Heating Season), kWh	1092	362	628	1031	0	531	9
(Cooling Season), kWh	4570	4560	4553	2079	0	709	24
Individual Customer Max.Dmd., kW	6.41	22.8	6.41	0.77	0.485	0.747	0.962
Contribution to System Peak, kW	4.49	0.06	4.49	0.20	0	0.07	0
1990 Installed Cost, $	3696	9004	12,254	586	933	4005	4070
Demand Related Costs:							
Contrib. to Sys. Peak, $360.68/kW	1619.45	21.64	1619.45	72.14	0	25.25	0
Meter Cost,$83.88/yr	0	83.88	0	0	83.88	0	83.88
Energy Related Costs:							
Off-Peak Consumption, 9.93 ¢/kWh	212.01	354.40	154.21	37.34	364.33	24.73	149.05
On-Peak Consumption,							
(Heating Season), 37.33 ¢/kWh	407.64	135.13	234.43	384.87	0	198.22	3.36
(Cooling Season), 24.46 ¢/kWh	1117.82	1115.38	1113.66	508.52	0	173.42	5.87
Subtotal Cost-to-Serve, $	3356.92	1688.79	3121.76	1002.87	448.21	421.62	242.16
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	496.74	1210.21	1646.96	78.81	125.44	538.33	547.09
TOTAL ANNUAL COST, $	3854.	2921.	4769.	1082.	574.	960.	789.

Table 7-23. Annual Costs for Solar Air Conditioning for Daytona Beach (1995)

Consumption and Cost Data	Resistance Space Heating Conventional Air Conditioning	Solar Space Heating, 55.7m^2 Solar Air Conditioning	Solar Space Heating, 55.7m^2 Solar Air Conditioning with Off-Peak Hot Storage
Annual Consumption, kWh	7797	15,231	16,003
Off-Peak Consumption kWh	2135	3,869	15,058
On-Peak Consumption			
(Heating Season), kWh	1092	372	249
(Cooling Season), kWh	4570	10,990	1,923
Individual Customer Max.Dmd., kW	6.41	10.90	15.36
Contribution to System Peak, kW	4.49	0.06	0.06
1990 Installed Cost, $	3,696	47,089	54,236
Demand Related Costs:			
Contrib. to Sys. Peak, $360.68 kW	1619.45	21.64	21.64
Meter Cost, $83.88/yr	0	0	83.88
Energy Related Costs:			
Off-Peak Consumption, 9.93 ¢/kWh	212.01	384.19	1495.26
On-Peak Consumption			
(Heating Season), 37.33 ¢/kWh	407.64	138.87	92.95
(Cooling Season), 24.46 ¢/kWh	1117.82	2688.15	470.37
Subtotal Cost-to-Serve, $	3356.92	3232.85	2164.10
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	496.74	6328.76	7235.00
TOTAL ANNUAL COST, $	3854.	9562.	9399.

higher than that of the solar water heater without off-peak storage throughout the period investigated. Solar water heating without off-peak storage is therefore optimum for Daytona Beach.

Solar Air Conditioning (combined with Solar Space Heating)

The cost to serve a solar heating and air conditioning system is slightly lower than that to serve a conventional heating and air conditioning system, probably within the accuracy of the analysis. Adding off-peak storage to the solar system reduces the cost-to-serve by one-third. However, the total cost of solar space conditioning is three times that of using a conventional system in 1985 and 2.5 times in 1995. The addition of off-peak storage changes the total cost by 2% only which is probably less than the accuracy of the analysis. One can conclude that solar heating and air conditioning with electrical back-up is not likely to be commercially viable in San Diego in the foreseeable future, even with the aid of off-peak storage.

Combined solar water and space heating systems were not analyzed for Daytona Beach. They were, however, analyzed for San Diego, CA in Section 8. The results to be found there are reasonably well applicable to Daytona Beach as well.

8. ENERGY/COST PERFORMANCE FOR SAN DIEGO, CALIFORNIA

8.1 TYPICAL HOME

The typical home chosen for this study is a well insulated 148 m^2 (1600 ft^2) four bedroom home located in San Diego, California. The house is insulated to comply with the Thermal Performance Guidelines for One and Two Family Dwellings (Ref. 8-1) assuming an energy cost of 5.3 ¢/kWh). Average annual climatic data used are 1500 heating degree days and 620 cooling hours. Based on the Guidelines, the house is insulated to a value of R-19 in the ceiling, R-12 in the walls, has single glazed windows and R-7.5 around the perimeter of the concrete slab floor. Due to the limitations of the TRNSYS (Ref. 8-2) heating load model, a value of R-22 was used for the ceiling insulation. Overall heat loss coefficient of the house is 0.29 kW/°C (556 Btu/hr°F).

8.2 BASIC DATA

8.2.1 Weather Data

The basic analysis was performed for a home in the San Diego, California area. Weather data recorded at the San Diego's Lindbergh Airport were used in this analysis. The climate at this location is strongly influenced by its proximity to the Pacific Ocean. This influence leads to more moderate heating and cooling loads than those found at the inland locations that comprise the majority of the San Diego Gas and Electric Company's (SDGE) service territory. However, this was the only location within the SDGE service territory for which complete solar radiation data was available.

The typical year was chosen after comparing monthly and annual heating degree days for the years 1952-1964 for San Diego with average monthly and annual values. Data for specific years were obtained from Climatological Data - National Summary, (Ref. 8-3), and average data were taken from the Climatic Atlas of The United States (Ref. 8-4). The monthly and annual values for the year 1964 were found to correspond most closely to the average.

8.2.2 Heating Season

The space heating season is defined by the San Diego Gas and Electric Company to last from November 1 through April 30. For this reason, the performance of various heating systems were simulated for January 1 - April 30 and November 1 - December 31 of the 1964 calendar year.

The peak load experienced by San Diego Gas and Electric Company during 1964 occurred at 6 pm on December 22.

8.3 ENERGY ANALYSIS OF SPACE HEATING SYSTEMS (For details, see Appendix B)

8.3.1 Conventional Resistance Space Heating - Base System

The base is an electrical resistance duct heater. The electrical energy consumption of this system is equal to the heating load of the house. The annual energy consumption of this system is 13.1 GJ (3636 kWh). Of this total 4.0 GJ (1106 kWh) occurred during the on-peak period (7am - 11pm) and 9.1 GJ (2530 kWh) occurs during the off-peak period. Table 8-1 lists the monthly electrical consumption of this system during the on- and off-peak periods. The average hourly consumption and peak load for each month are given in Table 8-2.

Table 8-1. Energy Consumed for Resistance Space Heating (kWh)
San Diego, California

Month	On-Peak	Off-Peak	Total
January	250	581	831
February	110	414	524
March	130	373	503
April	86	279	365
November	177	350	527
December	353	533	886
Annual Total	1106	1406	3636

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

RESISTANCE SPACE HEATING

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.775	0.149	0.458	0.348	0.345	0.000	0.000	0.000	0.000	0.000	0.627	1.095
2	1.346	0.421	0.706	0.588	0.520	0.017	0.000	0.000	0.000	0.000	0.932	1.551
3	1.939	0.886	1.065	0.799	0.694	0.068	0.000	0.000	0.000	0.000	1.197	1.935
4	2.425	1.489	1.387	1.080	0.913	0.210	0.000	0.000	0.000	0.000	1.381	2.145
5	2.744	2.200	1.656	1.380	1.187	0.363	0.000	0.000	0.000	0.000	1.552	2.324
6	2.921	2.792	1.931	1.578	1.432	0.512	0.000	0.000	0.000	0.018	1.756	2.482
7	3.050	3.129	2.204	1.708	1.602	0.676	0.000	0.000	0.000	0.057	1.933	2.614
8	3.162	3.253	2.313	1.634	1.495	0.671	0.000	0.000	0.000	0.107	2.022	2.697
9	3.016	2.594	1.945	1.317	1.116	0.483	0.000	0.000	0.005	0.114	1.939	2.680
10	2.191	1.284	1.199	0.835	0.705	0.261	0.000	0.000	0.005	0.056	1.432	2.190
11	1.072	0.338	0.511	0.370	0.352	0.096	0.000	0.000	0.000	0.009	0.736	1.347
12	0.370	0.029	0.140	0.110	0.127	0.022	0.000	0.000	0.000	0.000	0.274	0.714
13	0.120	0.003	0.035	0.025	0.044	0.006	0.000	0.000	0.000	0.000	0.087	0.385
14	0.068	0.000	0.000	0.005	0.018	0.000	0.000	0.000	0.000	0.000	0.051	0.226
15	0.055	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000	0.045	0.143
16	0.031	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.039	0.114
17	0.022	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.042	0.119
18	0.034	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.058	0.163
19	0.058	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	0.074	0.241
20	0.098	0.000	0.000	0.000	0.026	0.000	0.000	0.000	0.000	0.000	0.098	0.336
21	0.139	0.000	0.002	0.000	0.041	0.000	0.000	0.000	0.000	0.000	0.163	0.487
22	0.237	0.000	0.050	0.016	0.063	0.000	0.000	0.000	0.000	0.000	0.246	0.670
23	0.363	0.000	0.181	0.103	0.119	0.000	0.000	0.000	0.000	0.000	0.343	0.817
24	0.493	0.031	0.331	0.227	0.190	0.000	0.000	0.000	0.000	0.000	0.449	0.933
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	4.175	3.867	3.719	2.844	2.800	1.924	0.000	0.000	0.148	1.865	4.586	4.228
DAY	15	7	8	7	7	10	10	10	19	27	15	30
HOUR	8	8	8	7	7	6	6	6	9	8	8	8

@

8.3.2 Resistance Space Heating with Off-Peak Storage

A 0.93 m^3 (250 gal) insulated water tank with a 15.0 kW (52,000 Btu/hr) resistance heating coil is used to provide off-peak energy storage. During the off-peak period the tank is heated to set temperatures based on the 12 pm temperature as described in Section 3. With insulation, the heat loss coefficient of the tank is 0.417 W/(m^2°C), (0.73 Btu/hr ft^2°F of R-13.6).

During the peak period, the hot water from the tank is circulated through a heat exchange coil in the air duct where it heats the air being delivered to the load. Figure 4-1 shows a schematic representation of this system. Circulation of the hot water from the off-peak storage tank through the coil in the hot air duct is provided by 0.95 litres/second (7 gpm) pump driven by a 60 watt electrical motor. The energy consumption of this pump during peak hours is determined by multiplying this power rating by the fraction of time that the pump is operating.

Simulation Results

The yearly energy consumption of this system is 14.6 GJ (4063 kWh), an increase of 1.5 GJ (694 kWh) over the yearly energy consumption of the conventional resistance heating system. This 11% increase is due to

- stand-by heat loss from the off-peak storage tank and
- energy required to pump the stored hot water through the coil.

Ninety-nine percent (4027 kWh) of the total energy consumption occurs during the off-peak period. Only one percent (37 kWh) of the total consumption occurs during on- and off-peak periods is listed in Table 8-3. Hourly profiles of energy consumption for this system are given in Table 8-4.

8.4 ENERGY ANALYSIS OF SPACE AND WATER HEATING SYSTEMS

8.4.1 Resistance Space and Water Heating

This system simply combines the performance of an electrical resistance duct heater for space heating and a conventional electric 0.23 m^3

Table 8-3. Energy Consumed for Resistance Space Heating With Off-Peak Storage (kWh) San Diego, California

Month	On-Peak	Off-Peak	Total
January	7	910	917
February	3	600	603
March	4	562	566
April	4	422	426
November	7	613	620
December	12	920	932
Annual Total	37	4027	4063

(60 gal) water heater. Energy consumption of the duct heater is equal to the house heating load (assuming 100% efficiency) while the consumption of the water heater is equal to the hot water load plus stand-by heat loss from the water tank. The water heating load used in this simulation was 227ℓ (60 gallons) per day being heated from 17.8°C (64°F) to 60°C (140°F).

Simulation Results

Annual energy consumption for this combined system was 27.1 GJ (7533 kWh). Of this 17.1 GJ (4751 kWh) occurred during the on-peak period (7am - 11pm)and 10.0 GJ (2772 kWh) occurred during the off-peak period (11pm - 7am). Monthly electrical consumption of this system during the on- and off-peak periods is listed in Table 8-5. Average hourly consumption for this system is shown in Table 8-6.

8.4.2 Conventional Solar Space and Water Heating System

Since the heating season in San Diego is relatively short and the space heating load is fairly small, it seems doubtful that anyone would install a solar system for space heating only. We therefore combined domestic water preheating with the solar space heating systems to utilize solar energy throughout the entire year.

Table 8-4. Average Hourly Profile for Resistance Space Heating System with Off-Peak Storage for San Diego, California

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

OFF-PEAK RESISTANCE HEATING SYSTEM

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
2	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
3	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
4	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
5	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
6	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
7	3.681	2.673	2.256	1.747	0.000	0.000	0.000	0.000	0.000	0.000	2.555	3.698
8	0.059	0.059	0.055	0.055	0.002	0.000	0.000	0.000	0.000	0.000	0.053	0.059
9	0.059	0.059	0.055	0.053	0.000	0.000	0.000	0.000	0.000	0.000	0.045	0.059
10	0.057	0.049	0.049	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.041	0.059
11	0.037	0.006	0.026	0.027	0.000	0.000	0.000	0.000	0.000	0.000	0.024	0.052
12	0.013	0.002	0.007	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.028
13	0.007	0.000	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.022
14	0.004	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.017
15	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.016
16	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.015
17	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.015
18	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.017
19	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.020
20	0.006	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.008	0.025
21	0.010	0.000	0.007	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.027
22	0.011	0.000	0.013	0.008	0.000	0.000	0.000	0.000	0.000	0.000	0.012	0.027
23	0.016	0.004	0.013	0.013	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.029
24	3.626	2.715	2.171	1.723	0.000	0.000	0.000	0.000	0.000	0.115	2.502	3.635
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	7.014	5.014	5.603	3.933	0.059	0.000	0.000	0.000	0.000	3.569	7.400	7.175
DAY	14	25	7	5	1	1	1	1	1	31	14	29
HOUR	24	24	24	24	8	8	8	8	8	24	24	24

Table 8-5. Energy Consumed for Resistance Space and Water Heating

Month	On-Peak	Off-Peak	Total
January	566	566	1132
February	397	426	823
March	444	391	835
April	387	302	689
May	307	28	335
June	297	27	324
July	307	28	335
August	307	28	335
September	297	27	324
October	307	28	335
November	479	369	848
December	666	552	1218
	4761	2772	7533

The *conventional solar space and water heating* system is shown schematically in Figure 8-1. The solar collector array consists of 9.69 m^2 (104.3 ft^2) of single-glazed flat plate solar collectors tilted 40° from the horizontal. Water from an insulated 0.78 m^3 (206 gallon) storage tank is circulated through the collectors by a pump controlled by a differential thermostat. When space heating is required, hot water from the storage tank is circulated through a coil in the air duct of the house. Preheating of the domestic hot water is provided by running the incoming cold water from the city mains through a heat exchange coil located in the solar storage tank. This preheated water is then fed to a conventional 0.23 m^3 (60 gallon) electric water heater where it is heated to the required temperature of 60°C (140°F).

Simulation Results

Annual energy consumption for this system was 9.2 GJ (2558 kWh) of which 6.0 GJ (1673 kWh) occurred during the on-peak period and 3.2 GJ (885 kWh) occurred during the off-peak period. The reduction in electrical energy consumption for this system compared to the resistance

Table 8-6. Average Hourly Consumption for Resistance Space and Water Heating System in San Diego, California

AVERAGE DAILY PROFILE FOR 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

RESISTANCE HEATING AND HOT WATER SYSTEM

HOT WATER LOAD= 60 GALLONS PER DAY

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1.418	0.512	0.797	0.679	0.096	0.091	0.091	0.091	0.091	0.091	1.023	1.641
2	1.939	0.886	1.065	0.799	0.000	0.000	0.000	0.000	0.000	0.000	1.197	1.935
3	2.425	1.489	1.387	1.080	0.000	0.000	0.000	0.000	0.000	0.000	1.381	2.145
4	2.744	2.200	1.656	1.380	0.000	0.000	0.000	0.000	0.000	0.000	1.552	2.324
5	2.921	2.792	1.931	1.578	0.000	0.000	0.000	0.000	0.000	0.000	1.756	2.482
6	3.151	3.230	2.304	1.809	0.101	0.101	0.101	0.101	0.101	0.101	2.034	2.715
7	3.535	3.627	2.687	2.008	0.374	0.374	0.374	0.374	0.374	0.374	2.396	3.070
8	3.693	3.270	2.622	1.993	0.677	0.677	0.677	0.677	0.677	0.677	2.616	3.357
9	3.056	2.150	2.064	1.700	0.866	0.866	0.866	0.866	0.866	0.866	2.298	3.056
10	1.881	1.146	1.319	1.178	0.808	0.808	0.808	0.808	0.808	0.808	1.544	2.155
11	0.952	0.611	0.722	0.693	0.582	0.582	0.582	0.582	0.582	0.582	0.856	1.296
12	0.545	0.428	0.459	0.450	0.425	0.425	0.425	0.425	0.425	0.425	0.512	0.810
13	0.557	0.489	0.489	0.495	0.489	0.489	0.489	0.489	0.489	0.489	0.540	0.716
14	0.443	0.388	0.398	0.390	0.388	0.388	0.388	0.388	0.388	0.388	0.434	0.531
15	0.302	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.271	0.310	0.385
16	0.261	0.239	0.239	0.239	0.239	0.239	0.239	0.239	0.239	0.239	0.280	0.357
17	0.372	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.338	0.395	0.501
18	0.664	0.607	0.607	0.607	0.607	0.607	0.607	0.607	0.607	0.607	0.680	0.848
19	1.152	1.055	1.055	1.055	1.055	1.055	1.055	1.055	1.055	1.055	1.153	1.391
20	1.255	1.116	1.118	1.116	1.116	1.116	1.116	1.116	1.116	1.116	1.279	1.603
21	1.090	0.853	0.903	0.869	0.853	0.853	0.853	0.853	0.853	0.853	1.100	1.524
22	1.010	0.647	0.828	0.750	0.647	0.647	0.647	0.647	0.647	0.647	0.990	1.464
23	1.027	0.565	0.865	0.762	0.534	0.534	0.534	0.534	0.534	0.534	0.984	1.467
24	1.114	0.489	0.810	0.720	0.340	0.340	0.340	0.340	0.340	0.340	0.966	1.507
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	4.817	4.239	4.094	3.153	1.116	1.116	1.116	1.116	1.116	1.116	5.056	4.883
DAY	15	7	8	7	1	1	1	1	1	1	15	30
HOUR	8	7	7	7	20	20	20	20	20	20	8	8

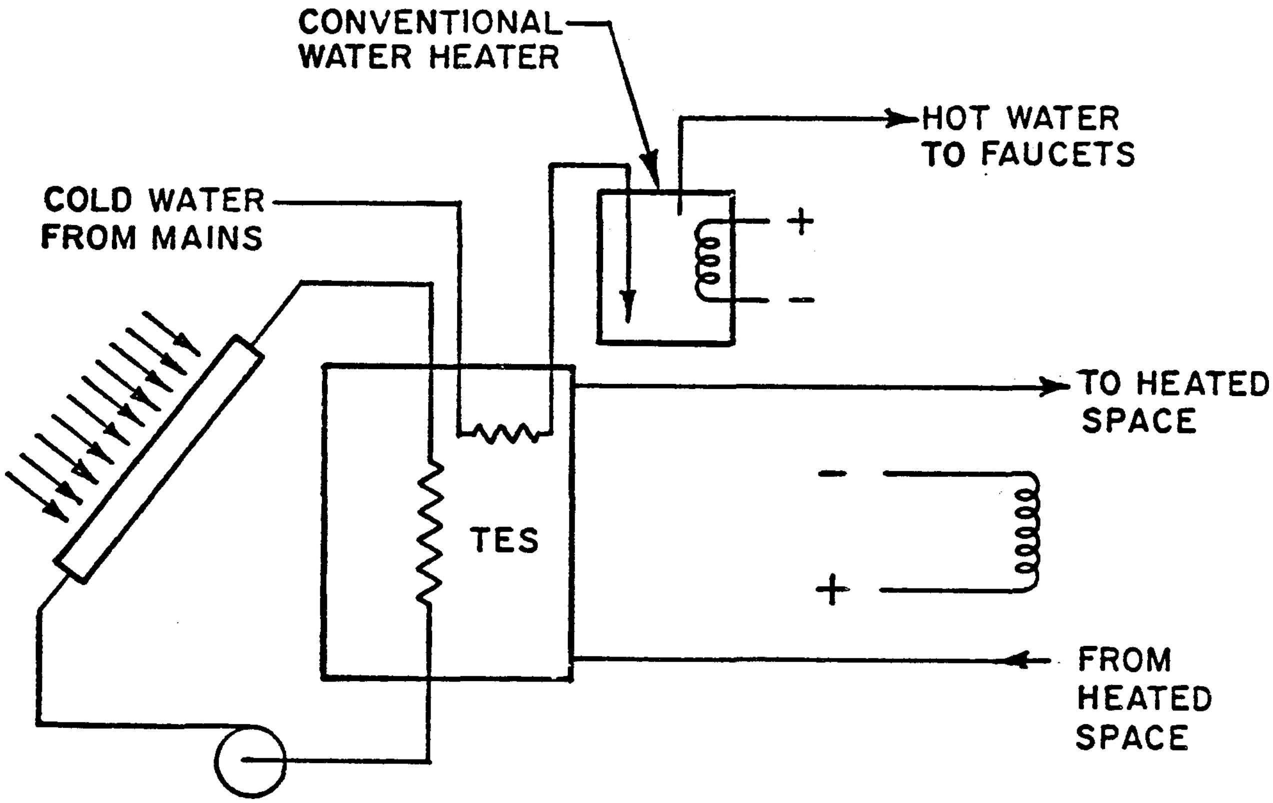

Figure 8-1. Conventional Solar Space Heating and Hot Water System

space and water heating system means that 66% of the total load was supplied by the solar system. Table 8-7 lists the energy consumption during the on- and off-peak periods along with the solar system performance for each month.

The solar system efficiency is defined as the amount of solar derived energy delivered to the load divided by the total solar energy incident on the collectors. The low solar system efficiencies for the summer months are due to the fact that the water heating load is too low to utilize all of the energy collected by the solar system. This causes the solar storage tank temperature to rise leading to low collector efficiency and increased heat loss from the tank.

An average hourly profile of the energy consumption of this system is listed in Table 8-8.

Table 8-7. Performance of Conventional Solar Heating System
San Diego, California

	Auxiliary Energy Consumption				
Month	On-Peak (kWh)	Off-Peak (kWh)	Total (kWh)	Solar[1/] Fraction (%)	Solar System[2/] Efficiency (%)
January	395	225	620	45	37
February	154	40	194	76	39
March	155	78	233	72	35
April	127	60	187	73	33
May	20	3	23	93	22
June	26	2	28	92	22
July	7	0	7	98	23
August	16	1	17	95	24
September	8	0	8	98	24
October	14	1	15	96	25
November	239	159	398	53	33
December	512	316	828	32	36
Annual Total	1673	885	2558	66	29

1/ Solar Fraction = $\dfrac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$

2/ Solar System Efficiency = $\dfrac{\text{Solar Energy Delivered to Load}}{\text{Total Incident Energy on the Collectors}}$

8.4.3 Solar Space and Water Heating System With Separate Off-Peak Storage

The *solar heating and hot water with separate off-peak storage* system is shown in Figure 8-2. This system is identical to the conventional solar space and water heating system with a 0.926 m^3 (245 gallon) off-peak storage tank for space heating added and a 0.303 m^3 (80 gallon) hot water heater with a clock timer replacing the smaller conventional electric water heater. During the heating season, the off-peak storage tank is heated during the 11pm to 7am period to a set temperature based

Table 8-8. Average Hourly Profiles for Solar Space and Water Heating System in San Diego, California

SPACE HEATING AVERAGE DAILY PROFILE FOR 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SOLAR SPACE HEATING AND HOT WATER PREHEAT

SOLAR COLLECTOR AREA = 104 FT**2

HOT WATER LOAD= 60 GALLONS PER DAY

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	0.388	0.045	0.062	0.073	0.063	0.023	0.000	0.011	0.002	0.010	0.334	0.983
2	0.497	0.030	0.071	0.111	0.011	0.006	0.000	0.003	0.001	0.003	0.380	0.985
3	0.591	0.029	0.118	0.152	0.000	0.000	0.000	0.000	0.000	0.000	0.429	0.983
4	0.755	0.043	0.230	0.175	0.000	0.000	0.000	0.000	0.000	0.000	0.586	1.048
5	0.964	0.151	0.455	0.252	0.000	0.000	0.000	0.000	0.000	0.000	0.806	1.265
6	1.535	0.412	0.676	0.444	0.000	0.000	0.000	0.000	0.000	0.000	0.985	1.744
7	2.155	0.658	0.838	0.658	0.006	0.008	0.000	0.004	0.001	0.004	1.346	2.258
8	2.997	1.270	1.253	0.807	0.024	0.030	0.000	0.015	0.003	0.014	1.720	2.753
9	3.237	1.807	1.328	0.881	0.046	0.060	0.000	0.031	0.006	0.028	1.806	2.994
10	2.565	1.033	0.905	0.752	0.066	0.089	0.003	0.047	0.013	0.046	1.528	2.648
11	1.020	0.472	0.415	0.468	0.078	0.099	0.024	0.062	0.029	0.061	0.782	1.576
12	0.524	0.262	0.263	0.303	0.065	0.089	0.029	0.059	0.033	0.055	0.351	0.900
13	0.297	0.155	0.158	0.164	0.054	0.073	0.031	0.051	0.034	0.045	0.201	0.545
14	0.255	0.118	0.120	0.136	0.053	0.068	0.033	0.048	0.034	0.042	0.175	0.438
15	0.182	0.072	0.080	0.097	0.047	0.053	0.034	0.042	0.034	0.036	0.135	0.314
16	0.113	0.043	0.051	0.064	0.040	0.042	0.034	0.037	0.033	0.033	0.103	0.230
17	0.085	0.036	0.043	0.052	0.036	0.036	0.033	0.033	0.031	0.028	0.092	0.209
18	0.081	0.010	0.029	0.043	0.020	0.028	0.014	0.018	0.006	0.006	0.096	0.259
19	0.153	0.013	0.034	0.052	0.013	0.021	0.000	0.005	0.000	0.007	0.145	0.414
20	0.274	0.032	0.066	0.099	0.026	0.041	0.000	0.012	0.000	0.013	0.230	0.660
21	0.330	0.053	0.082	0.119	0.032	0.050	0.000	0.018	0.001	0.017	0.274	0.817
22	0.315	0.058	0.079	0.108	0.028	0.044	0.000	0.018	0.002	0.016	0.261	0.848
23	0.314	0.054	0.077	0.101	0.023	0.037	0.000	0.016	0.003	0.014	0.245	0.896
24	0.363	0.055	0.076	0.131	0.020	0.034	0.000	0.016	0.003	0.014	0.262	0.940
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	4.539	3.956	3.931	2.928	1.534	0.373	0.034	0.253	0.154	0.311	4.797	4.628
DAY	15	15	8	3	1	16	1	3	18	26	15	30
HOUR	9	8	8	8	1	11	11	11	11	10	8	9

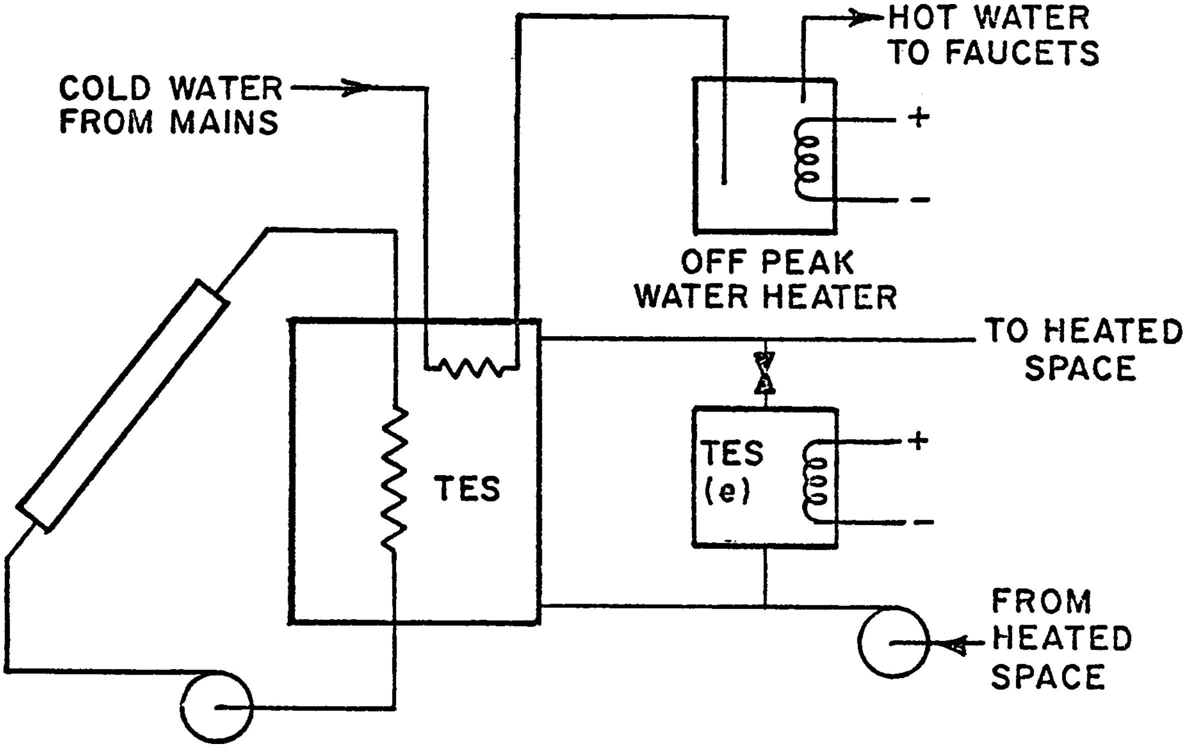

Figure 8-2. Solar Space and Water Heating System with Off-Peak Storage

on the 11pm ambient temperature each night as described in Section 3.

When a heating load occurs during the on-peak period from 7 am to 11 pm, it is supplied from the solar storage tank if its temperature is above 35°C (95°F). If that temperature is below 35°C (95°F) the space heating load is supplied from the off-peak storage tank.

The off-peak hot water heater is heated to 70°C (158°F) during the 11 pm to 7 am period each night.

Simulation Results

Annual energy consumption for this system was 13.4 GJ (3733 kWh), of which 1.5 GJ (425 kWh) occurred during the on-peak period and 11.9 GJ (3308 kWh) occurred during the off-peak period. On- and off-peak period consumption along with solar system performance are listed by month in Table 8-9. Average hourly consumption is listed for each month in Table 8-10.

Table 8-9. Performance of Solar Space and Water Heating System With Separate Off-peak Storage in San Diego, California

Month	Auxiliary Energy Consumption On-Peak (kWh)	Off-Peak (kWh)	Total (kWh)	Solar[1/] Fraction (%)	Solar System[2/] Efficiency (%)
January	36	721	757	33	35
February	33	296	329	60	38
March	37	314	351	58	34
April	36	262	298	57	31
May	36	67	103	69	19
June	34	82	116	64	20
July	36	21	57	83	20
August	36	52	88	74	21
September	35	27	62	81	20
October	36	46	82	76	22
November	35	507	542	36	32
December	35	913	948	22	35
Annual Total	427	3308	3734	50	27

1/ Solar Fraction $= \frac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$

2/ Solar System Efficiency $= \frac{\text{Solar Energy Delivered to Load}}{\text{Total Incident Energy on the Collectors}}$

8.5 ENERGY ANALYSIS OF SPACE COOLING SYSTEMS

The performance of three solar air conditioning (A/C) systems was compared with that of a conventional vapor compression unit. Cooling loads were calculated for the typical house described in Subsection 8.1

Table 8-10. Average Hourly Energy Consumption for Solar Space and Water Heating System With Separate Off-Peak Storage for San Diego, California

AVERAGE DAILY PROFILE FOR 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SOLAR HEATING & HOT WATERS SYSTEM WITH TWO
OFF-PEAK STORAGE TANKS ONE FOR HEATING AND ONE FOR HOT WATER
HOT WATER IS ALWAYS PREHEATED IN THE SOLAR TANK

HOT WATER LOAD= 60 GALLONS PER DAY

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
2	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
3	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
4	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
5	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
6	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
7	2.909	1.317	1.270	1.090	0.274	0.342	0.085	0.210	0.114	0.175	2.122	3.665
8	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
9	0.079	0.090	0.082	0.074	0.063	0.060	0.061	0.060	0.061	0.062	0.071	0.068
10	0.088	0.090	0.089	0.085	0.077	0.066	0.081	0.072	0.078	0.077	0.087	0.081
11	0.090	0.092	0.090	0.091	0.085	0.078	0.088	0.082	0.086	0.085	0.090	0.085
12	0.092	0.093	0.091	0.092	0.090	0.086	0.090	0.090	0.089	0.089	0.091	0.089
13	0.091	0.093	0.092	0.093	0.092	0.093	0.093	0.091	0.091	0.090	0.090	0.091
14	0.090	0.093	0.092	0.093	0.093	0.093	0.093	0.091	0.092	0.089	0.089	0.090
15	0.092	0.093	0.092	0.092	0.092	0.091	0.093	0.090	0.092	0.089	0.089	0.086
16	0.087	0.090	0.088	0.089	0.090	0.087	0.092	0.088	0.089	0.083	0.085	0.078
17	0.060	0.063	0.069	0.075	0.070	0.075	0.069	0.069	0.063	0.061	0.062	0.060
18	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
19	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
20	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
21	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
22	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
23	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
24	2.881	1.336	1.234	1.099	0.249	0.341	0.086	0.214	0.109	0.273	2.054	3.790
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	7.042	2.889	3.889	3.531	0.895	0.665	0.182	0.526	0.358	3.097	7.375	7.914
DAY	14	16	23	23	1	15	9	14	18	31	17	29

using weather data from 1964 for San Diego, California. Two types of solar air conditioning systems were considered. A schematic diagram of a conventional solar air conditioner is shown in Figure 4-24 and a diagram of a solar air conditioner with off-peak hot storage is shown in Figure 4-26. In both diagrams, the cooling tower, which would be required, is not shown.

The conventional solar A/C operates with hot water from the solar storage tank whenever possible. When solar heat is not available, valve V-1 bypasses the solar storage, and the auxiliary heater supplies energy to the air conditioner. The solar A/C with off-peak hot water storage also uses solar energy whenever possible. However, when solar storage is depleted, heat is obtained from the off-peak storage tank. The auxiliary electric heater in the off-peak storage tank only operates between 12 midnight and 8 AM. The off-peak storage tank is sized so that all cooling loads during the day can be met with heat from the off-peak storage tank. Consequently, the only electricity usage by this system during the day is by pumps and fans. These systems are discussed in more detail in Appendix B.

Two conventional solar air conditioners were simulated: one with 27.9 m^2 (300 ft^2) of collector area and the other with 55.8 m^2 (600 ft^2) of collector area. The solar A/C with off-peak hot storage had 27.9 m^2 (300 ft^2) of collector area. In each case, solar storage had a capacity equivalent to 81.5 kg/m^2 (2 gal/ft^2) of collector area. The capacity of the off-peak hot storage was 2.25 m^3 (594 gal).

Since the collector area used for the solar air conditioning systems (55.8 m^2 (600 ft^2) and 27.9 m^2 (300 ft^2)) are so much larger than the area used for solar space and water heating (9.68 m^2 (104 ft^2)) it was necessary to simulate the solar heating system performance at these larger collector areas so that the annual performance of a combined solar heating cooling system was obtained for these two large collector areas.

Simulation Results

One-hundred percent of the space and water heating requirements are provided by solar system with 55.8 m^2 (600 ft^2). The only energy required by this system during **the** heating season is to run the pumps that circulate the working fluid between the collectors and storage, and between storage and the heating load. A solar space and water heating system with 27.9 m^2 (300 ft^2) of collectors provides 98.5% of the heating requirements. Therefore in addition to the energy requirements of the pumps this system uses a small amount of auxiliary energy for those few short periods that the solar system cannot meet the entire heating load. All of this auxiliary energy requirements occurs during the off-peak period (11 pm - 7 am) during the heating season.

Monthly usage for the conventional compression air conditioning system and three air conditioning systems is shown in Table 8-10. Monthly energy usage is given for solar A/C systems with 55.8 m^2 (600 ft^2) and 27.9 m^2 (300 ft^2) of solar collector area. Energy usage is also presented for a solar A/C system with off-peak storage and 27.9 m^2 (300 ft^2) of collector area. It can be seen that the solar system with 55.8 $m2$ (600 ft^2) of collector area would have a lower seasonal electric energy use than the conventional compression air conditioner. The conventional solar A/C with 27.9 m^2 (300 ft^2) of collector area has a greater seasonal electric energy usage than the conventional vapor compression A/C. The use of off-peak hot storage decreases electricity usage during the on-peak period slightly but at the expense of a much greater seasonal electricity usage. Since most of the cooling requirements occur during the day, only the system with off-peak storage has a significant electricity usage during the off-peak period.

Table 8-11. Air Conditioning System Monthly Energy Usage (kWh)
San Diego, California

Month	Compression A/C		Conventional Solar A/C with 55.8 m^2 of Collector Area		Conventional Solar A/C with 27.9 m^2 of Collector Area		Solar A/C with 27.9 m^2 Collector Area and Off-Peak Storage	
	On Peak	Off Peak	On Peak	Off Peak	On Peak	Off Peak	On Peak	Off Peak
April	20	0	19	0	13	0	27	88
May	31	0	40	0	31	0	46	81
June	89	0	78	0	94	0	76	94
July	274	0	180	0	483	0	155	433
August	154	0	147	0	286	0	131	254
September	26	0	42	0	33	0	48	78
October	86	0	64	0	126	0	63	157
Total	680	0	568	0	1064	0	546	1195
	680		586		1064		1741	

The monthly peak electric demands for the conventional and solar systems are shown in Table 8-11. The magnitudes of the demands and the day and hour (Pacific Standard Time) when they occur are given. Comparing the peaks of the conventional solar A/C with 55.8 m^2 (600 ft^2) of collector area to the compression A/C, it can be seen that a solar air conditioning system with a sufficiently large array of collectors can reduce both peak demands and seasonal energy usage.

If the collector area is reduced to 27.9 m^2 (300 ft^2), the conventional solar A/C will have higher peaks than the compression A/C. As shown in Table 8-12, these peaks will occur mainly during the middle of the day. By charging an off-peak storage tank, the solar A/C system peaks can be shifted to the early morning hours. During the day, the only equipment using electricity would then be pumps and fans.

System daily demand profiles averaged for each month are shown in Tables 8-13 through 8-16. That is, for a given month and hour, the demand shown is the average of all of the demands for that hour during the month.

Table 8-12. Air Conditioning System Monthly Peak Demands (kW)
San Diego, California

Month	Compression A/C			Conventional Solar A/C with 55.9 m^2 of Collector Area			Conventional Solar A/C with 27.9 m^2 of Collector Area			Solar A/C with 27.9 m^2 Collector Area and Off-Peak Storage
	Day	Hour	Demand	Day	Hour	Demand	Day	Hour	Demand	Demand*
April	14	18	1.87	15	13	0.58	15	13	0.43	1.44
May	25	18	1.51	25	14	0.57	20	13	8.94	7.32
June	30	18	1.72	30	14	0.58	25	14	0.43	0.47
July	11	18	1.85	15	15	0.58	29	18	8.37	2.43
August	19	16	1.35	20	16	0.58	10	18	8.94	5.42
September	3	17	0.95	20	11	0.56	1	19	3.84	2.28
October	19	16	2.71	25	14	0.58	10	14	0.43	0.47

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*These demands occur between the hours of midnight and 8 AM when the off-peak storage is being heated with electrical energy. When the off-peak storage is not being charged, the maximum demand is 0.47 kW.

The performance of the solar components for each solar air conditioning system are shown in Table 8-17.

Table 8-13. Average Hourly Energy Consumption for Conventional Air Conditioning for San Diego, California

AIR CONDITIONING AVERAGE DAILY PROFILES FOR APRIL THRU OCTOBER 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SYSTEM = CONVENTIONAL COMPRESSION AIR CONDITIONER

HOUR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBE
1	0.001	0.000	0.000	0.005	0.001	0.000	0.009
2	0.000	0.000	0.000	0.000	0.000	0.000	0.002
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.036	0.000	0.000	0.010
11	0.000	0.000	0.000	0.127	0.022	0.000	0.039
12	0.002	0.000	0.000	0.223	0.065	0.000	0.086
13	0.022	0.003	0.013	0.310	0.173	0.001	0.153
14	0.065	0.020	0.046	0.543	0.380	0.025	0.254
15	0.090	0.036	0.096	0.877	0.564	0.069	0.351
16	0.091	0.038	0.211	1.082	0.678	0.133	0.397
17	0.092	0.098	0.393	1.220	0.757	0.186	0.414
18	0.092	0.237	0.653	1.377	0.786	0.188	0.362
19	0.078	0.283	0.730	1.243	0.667	0.145	0.251
20	0.055	0.190	0.491	0.846	0.436	0.082	0.170
21	0.036	0.080	0.232	0.514	0.250	0.033	0.123
22	0.022	0.016	0.077	0.271	0.123	0.007	0.092
23	0.014	0.001	0.013	0.115	0.049	0.000	0.058
24	0.006	0.000	0.000	0.035	0.014	0.000	0.026

Table 8-14. Average Hourly Energy Consumption for Conventional Solar Air Conditioning with 55.8 m^2 Collector Area for San Diego, California

AIR CONDITIONING AVERAGE DAILY PROFILES FOR APRIL THRU OCTOBER 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SYSTEM = CONVENTIONAL SOLAR AIR CONDITIONER

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	0.014	0.000	0.000	0.054	0.027	0.000	0.029
2	0.000	0.000	0.000	0.000	0.000	0.000	0.013
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.001	0.000	0.000	0.000
10	0.003	0.000	0.005	0.114	0.019	0.000	0.015
11	0.037	0.021	0.028	0.180	0.082	0.022	0.037
12	0.081	0.061	0.060	0.216	0.156	0.068	0.108
13	0.091	0.086	0.084	0.335	0.265	0.099	0.157
14	0.092	0.078	0.104	0.447	0.392	0.114	0.191
15	0.054	0.028	0.117	0.523	0.407	0.075	0.162
16	0.033	0.029	0.150	0.467	0.413	0.119	0.152
17	0.032	0.111	0.214	0.471	0.425	0.154	0.180
18	0.032	0.136	0.332	0.475	0.455	0.172	0.184
19	0.032	0.191	0.348	0.475	0.459	0.186	0.182
20	0.032	0.199	0.348	0.475	0.457	0.172	0.168
21	0.032	0.191	0.344	0.475	0.436	0.148	0.163
22	0.030	0.124	0.295	0.471	0.367	0.071	0.121
23	0.016	0.027	0.127	0.417	0.245	0.014	0.105
24	0.016	0.000	0.014	0.209	0.124	0.000	0.084

Table 8-15. Average Hourly Energy Consumption for Conventional Solar Air Conditioning with 27.9 m^2 Collector Area for San Diego, California

AIR CONDITIONING AVERAGE DAILY PROFILES FOR APRIL THRU OCTOBER 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SYSTEM = CONVENTIONAL SOLAR AIR CONDITIONER

SOLAR COLLECTOR AREA = 27.9 m^2 (300 ft^2)

HOUR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	0.011	0.000	0.000	0.068	0.023	0.000	0.065
2	0.000	0.000	0.000	0.000	0.000	0.000	0.020
3	0.000	0.000	0.000	0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.000
7	0.000	0.000	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000
9	0.000	0.000	0.001	0.008	0.002	0.000	0.000
10	0.003	0.003	0.006	0.330	0.018	0.001	0.087
11	0.023	0.017	0.018	0.126	0.052	0.022	0.197
12	0.048	0.033	0.032	0.145	0.105	0.041	0.321
13	0.052	0.051	0.049	0.266	0.219	0.056	0.376
14	0.059	0.048	0.066	0.354	0.337	0.077	0.349
15	0.041	0.025	0.092	0.389	0.341	0.066	0.360
16	0.026	0.024	0.130	0.662	0.582	0.096	0.279
17	0.025	0.089	0.202	1.460	0.877	0.123	0.377
18	0.025	0.109	0.693	2.588	1.427	0.138	0.204
19	0.025	0.153	0.412	2.044	1.499	0.149	0.285
20	0.025	0.159	0.310	2.197	1.500	0.138	0.306
21	0.025	0.153	0.578	2.251	1.069	0.119	0.305
22	0.024	0.100	0.388	1.485	0.679	0.057	0.227
23	0.013	0.021	0.141	0.846	0.360	0.011	0.153
24	0.013	0.000	0.012	0.324	0.148	0.000	0.152

Table 8-16. Average Hourly Energy Consumption for Solar Air Conditioning with 27.9 m^2 Collector Area and Off-Peak Hot Storage for San Diego, California

AIR CONDITIONING AVERAGE DAILY PROFILES FOR APRIL THRU OCTOBER 1964

LOCATION: SAN DIEGO CALIFORNIA

ALL VALUES = KWH

SYSTEM = SOLAR AIR CONDITIONER WITH OFF PEAK HOT WATER STORAGE

SOLAR COLLECTOR AREA = 27.9 m^2 (300 ft^2)

HOUR	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	OCTOBER
1	0.366	0.327	0.393	1.787	1.023	0.327	0.632
2	0.366	0.327	0.393	1.787	1.023	0.327	0.632
3	0.366	0.327	0.393	1.787	1.023	0.327	0.632
4	0.366	0.327	0.393	1.787	1.023	0.327	0.632
5	0.366	0.327	0.393	1.787	1.023	0.327	0.632
6	0.366	0.327	0.393	1.787	1.023	0.327	0.632
7	0.366	0.327	0.393	1.787	1.023	0.327	0.632
8	0.366	0.327	0.393	1.787	1.023	0.327	0.632
9	0.000	0.000	0.001	0.004	0.001	0.000	0.000
10	0.003	0.002	0.006	0.092	0.017	0.001	0.015
11	0.023	0.017	0.018	0.119	0.052	0.020	0.031
12	0.048	0.033	0.031	0.146	0.108	0.041	0.073
13	0.052	0.051	0.050	0.243	0.195	0.057	0.103
14	0.060	0.049	0.067	0.330	0.294	0.079	0.138
15	0.042	0.027	0.095	0.393	0.311	0.066	0.134
16	0.026	0.024	0.134	0.396	0.342	0.098	0.126
17	0.025	0.093	0.174	0.380	0.342	0.125	0.145
18	0.025	0.109	0.272	0.380	0.366	0.138	0.147
19	0.025	0.156	0.278	0.380	0.367	0.150	0.146
20	0.025	0.159	0.278	0.380	0.367	0.138	0.135
21	0.025	0.156	0.277	0.380	0.352	0.123	0.132
22	0.025	0.105	0.244	0.378	0.300	0.060	0.097
23	0.013	0.023	0.108	0.344	0.202	0.012	0.085
24	0.481	0.469	0.481	0.644	0.574	0.469	0.539

Table 8-17. Performance of Solar Air Conditioning System Solar Components

	Conventional Solar A/C With 55.8 m^2 of Collector Area		Conventional Solar A/C With 27.9 m^2 of Collector Area		Solar A/C Wi Off-Peak Hot Storage	
	GJ	Btu x 10^6	GJ	Btu x 10^6	GJ	Btu x 1
Solar Radiation Incident on Collectors	225	213	112	107	112	107
Energy Collected and Delivered to Storage	15.6	14.8	11.6	11.0	11.6	11.0
Collector Efficiency	6.9%		10.4%		10.4%	
Energy Lost From Solar Storage	3.7	3.5	2.1	2.0	2.2	2.1
Solar Storage Efficiency	76.3%		81.9%		81.0%	
Auxiliary Energy Input to Off-Peak Storage					4.7	4.5
Energy Lost From Off-Peak Storage					2.4	2.3
Off-Peak Storage Efficiency					48.9%	

8.6 UTILITY COST COMPONENTS

San Diego Gas and Electric Company (SDGE) generously offered its cooperation in this project without reimbursement. This is a small utility serving 750,000 electric customers in 90 communities in the southwest corner of California. Its peak demand is 2 MW occurring in the summer. SDGE presently generates 80% of its power through gas and oil but, like all utilities, is under orders to eliminate the use of gas as a boiler fuel. After planning additional generation capacity at Kaiparowits in Utah and Sundesert in California, SDGE had to abandon both projects, largely due to pressure by environmentalists. Both power demand and energy demand are continuing to grow for this utility which is located in one of the major growth areas of the nation. SDGE is heavily strapped to meet its peak demand, must import power from outside the state, and is planning to import power from Mexico. Its demand costs are therefore comparably high.

Not having detailed SDGE data on the diversity of space conditioning equipment available, a diversity factor of (1/0.7) for both conventional and solar heating and air conditioning was assumed. Electric water heating is wide-spread throughout the SDGE territory. A contribution to systems peak from water heating of 0.4 kW per customer was assumed.

The installed capacity cost for units coming on line in 1985 is $1400/kW. The utility assumes that this cost increases at a rate of 8 percent per year yielding a cost of $3020/kW for capacity coming on line in 1995. The fuel cost escalation from present (1980) values was also assumed to be 8 percent per year.

SDGE was unable to provide a detailed breakdown of its costs of service similar to that obtained from PECo (see Section 6.3, Tables 6-1 through 6-4). These costs were, therefore, estimated by the same procedure as that used for Florida Power Corporation described in Section 7.6. The SDGE 1979 Annual Report (Ref. 8-5) and its residential off-peak tariff (Ref. 8-6) were used. The results of the calculations are shown in Table 8-18.

Table 8-18. San Diego Gas and Electric Company
Cost to Serve Data
(as determined by a Franklin Research
Center procedure)

Item	1980	1985	1995
Capacity Cost for Generation Coming On Line in Stated Year ($/kW)		1400	3020
Capital Recovery Factor		0.15	0.15
Annual Peak Demand Cost ($/kW)		210	453.37
Energy Cost, On-Peak (¢/kWh)	7.05	10.36	22.36
Energy Cost, Off-Peak* (¢/kWh)	3.08	4.53	9.78

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*Winter: 11 pm to 7 am
Summer: 12 pm to 9 am

8.7 DISCUSSION OF RESULTS

The results of the analyses are presented in Tables 8-19 for space and water heating systems and in Table 8-20 for air conditioning systems, both solar and conventional with and without off-peak storage, for the year 1985. Corresponding results for 1995 are given in Tables 8-21 and 8-22, respectively.

Solar Space Heating and Combined Space and Water Heating

Adding off-peak storage to a space heating system which is sufficient to eliminate all on-peak demands except for pumps and fans increases the annual energy consumption by 10% and reduces the cost to serve by almost 50%. The total cost (to the utility plus the homeowner) is increased by 12% in 1985, but this cost penalty has almost disappeared by 1995, demonstrating the increasing benefits of storage in the future. The cost to serve a solar space and water heating system is 43% lower than the cost to serve an equivalent electric resistance heating system while the total cost for solar heating is 28% higher in 1985 and 14% higher in 1995 than for resistance heating. The addition of off-peak storage to the solar system reduces its cost to serve by approximately one-half, but its total cost by 1% only in 1985 and 6% in 1995. Thus, off-peak storage appears to be a stand-off for heating in San Diego, unless utility costs change drastically.

Solar Heating and Air Conditioning

Since solar air conditioning requires a considerably larger collector ar in San Diego than solar space and water heating, a solar air conditioning system satisfies automatically virtually the entire heating load. Although the utility's cost to serve a solar heating/air conditioning system with 55.7 m^2 of solar collector is only 17% of the cost to serve an equivalent conventional system, the total system cost is five times as high in 1985 and four times as high in 1995. A system with a collector area of 28 m^2 (300 ft^2 is somewhat more economical. Its cost to serve is slightly higher (26% of that of a conventional system) but its total cost is 3.2 times as high in 198 and 2.7 times as high in 1995. The addition of off-peak storage to this system decreases the cost to serve minutely but increases the total cost by almost 20%. These relative costs are almost the same in 1995 as in 1985. Off-peak storage for air conditioning is, therefore, not to be recommended for this location. Solar air conditioning with electrical back-up and with or without off-peak storage will not become economically viable in San Diego in the foreseeable future unless the cost of electricity changes drastically.

Table 8-19. Annual Costs for Solar Space and Water Heating Systems in San Diego, California (1985)

Consumption and Cost Data	Resistance Space Heating (Base System)	Resistance Space Heating with Off-Peak Storage	Resistance Space & Water Heating (Base System)	Conventional Solar Space & Water Heating $9.68m^2$ ($104\ ft^2$)	Solar Space & Water Heating $9.68m^2$ with Off-Peak Storag
Annual Consumption, kWh	4316	4743	8213	3238	4413
Off-Peak Consumption, kWh	2087	4017	2775	888	3311
On-Peak Consumption, kWh	2229	726	5438	2350	1102
Individual Customer Max.Dmd., kW	4.59	7.40	5.06	4.80	7.91
Contribution to System Peak, kW	0.95	0.06	1.39	1.30	0.06
1980 Installed Cost, $	1823	4391	2182	8015	9980
Demand Related Costs:					
Contrib. to Sys. Peak, $210/kW	199.50	12.60	291.90	273.00	12.60
Energy Related Costs:					
On-Peak Consumption, 10.36 ¢/kWh	230.92	75.21	563.38	243.46	114.17
Off-Peak Consumption, 4.53 ¢/kWh	94.54	181.97	125.71	40.23	149.99
Subtotal Cost-to-Serve, $	524.96	269.78	980.98	556.69	276.76
Homeowner Loan Payment on Equipment (20 yr @ 12%) $	245.01	590.15	293.26	1077.22	1341.31
TOTAL ANNUAL COST, $	770.	860.	1274.	1634.	1618.

Table 8-20. Annual Costs for Solar Air Conditioning Systems in San Diego, California (1985)

Consumption and Cost Data	Resistance Space Heating & Conventional Air Conditioning (Base System)	Solar Heating, 55.7m^2, Solar Air Conditioning	Solar Heating, 27.9m^2, Solar Air Conditioning	Solar Heating, 27.9m^2, Solar Air Conditioning w/Off-Peak Storage
Annual Consumption, kWh	4316	782	1279	1954
Off-Peak Consumption, kWh	2087	108	115	1397
On-Peak, Consumption, kWh	2229	674	1164	557
Individual Customer Max.Dmd.,kW	4.59	0.58	8.94	7.32
Contribution to System Peak, kW	0.95	0.06	0.06	0.06
1980 Installed Cost, $	1823	27,408	17,203	20,433
Demand Related Costs:				
Contrib. to Sys. Peak, $210/kW	199.50	12.60	12.60	12.60
Energy Related Costs:				
On-Peak Consumption, 10.36 ¢/kWh	230.92	69.82	120.59	57.71
Off-Peak Consumption, 4.53 ¢/kWh	94.54	4.89	5.21	63.28
Subtotal Cost-to-Serve, $	524.96	87.32	138.40	133.59
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	245.01	3683.64	2312.08	2746.20
TOTAL ANNUAL COST, $	770.	3771.	2450.	2880.

Table 8-21. Annual Costs for Solar Space and Water Heating System in San Diego, California (1995)

Consumption and Cost Data	Resistance Space Heating (Base System)	Resistance Space Heating with Off-Peak Storage	Resistance Space & Water Heating (Base System)	Conventional Solar Space & Water Heating 9.68m^2(104 ft^2)	Solar Space & Water Heating 9.69m^2 with Off-Peak Storage
Annual Consumption, kWh	4316	4743	8213	3238	4413
Off-Peak, Consumption, kWh	2087	4017	2775	888	3311
On-Peak, Consumption, kWh	2229	726	5438	2350	1102
Individual Customer Max.Dmd., kW	4.59	7.40	5.06	4.80	7.91
Contribution to System Peak, kW	0.95	0.06	1.39	1.30	0.06
1990 Installed Cost, $	2969	7152	3554	13,056	16,256
Demand Related Costs:					
Contrib. to Sys. Peak, $453.37/kW	430.70	27.20	630.18	589.38	27.20
Energy Related Costs:					
On-Peak Consumption, 22.36 ¢/kWh	498.40	162.33	1215.94	525.46	246.41
Off-Peak Consumption, 9.78 ¢/kWh	204.11	392.86	271.40	86.85	323.82
Subtotal Cost-to-Serve, $	1133.21	582.40	2117.52	1201.69	597.43
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	399.03	961.29	477.69	1754.67	2184.86
TOTAL ANNUAL COST, $	1532.	1544.	2595.	2956.	2782.

Table 8-22. Annual Costs for Solar Air Conditioning Systems in San Diego, California (1995)

Consumption and Cost Data	Resistance Space Heating & Conventional Air Conditioning (Base System)	Solar Heating, 55.7m^2, Solar Air Conditioning	Solar Heating, 27.9m^2, Solar Air Conditioning	Solar Heating, 27.9m^2, Solar Air Conditioning w/Off-Peak Storage
Annual Consumption, kWh	4316	782	1279	1954
Off-Peak Consumption, kWh	2087	108	115	1397
On-Peak Consumption, kWh	2229	674	1164	557
Individual Customer Max.Dmd., kW	4.59	0.58	8.94	7.32
Contribution to System Peak, kW	0.95	0.06	0.06	0.06
1990 Installed Cost, $	2969	44,645	28,022	33,283
Demand Related Costs:				
Contrib. to Sys. Peak, $453.37/kW	430.70	27.20	27.20	27.20
Energy Related Costs:				
On-Peak Consumption, 22.36 ¢/kWh	498.40	150.71	260.27	124.55
Off-Peak Consumption, 9.78 ¢/kWh	204.11	10.56	11.25	136.63
Subtotal Cost-to-Serve, $	1133.21	188.47	298.72	288.38
Homeowners Loan Payment on Equipment (20 yr. @ 12%), $	399.03	6000.29	3766.16	4473.26
TOTAL ANNUAL COST, $	1532.	6189.	4065.	4762.

9. ENERGY PERFORMANCE FOR COLUMBUS, OHIO*

9.1 TYPICAL HOME

The house modelled for Columbus was the same as that used for Philadelphia. The overall heat loss coefficient of the house was 1035 kJ/hr•°C (543.9 Btu/hr•°F).

9.2 BASIC DATA

9.2.1 Weather Data

The typical year was chosen after comparing monthly and annual heating degree days for the years 1952-1964 for Columbus, Ohio with the average monthly and annual values. Data for specific years were obtained from Climatological Data - National Summary (Ref. 9-1), and average data were obtained from the Climatic Atlas of the United States (Ref. 9-2). The monthly and annual values for the year 1964 were found to correspond most closely to the average.

9.2.2 Heating Season

The length of the heating season was assumed to be the same as that for Philadelphia. That is, heating is required from October 1 through May 31. Consequently, the performance of various heating systems was simulated for January 1 - May 31, and October 1 - December 31 of the 1964 calendar year.

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*It had been intended to perform a complete energy and economic analysis for Columbus, Ohio similar to the analyses for Philadelphia, Daytona Beach, and San Diego contained in this report. However, delays in collecting the required electric utility data and shortages of time and money prevented the completion of this task. Only the energy analysis was completed and is presented in this Section. It is hoped to perform the economic analysis at a later date.

9.3 ENERGY ANALYSIS OF SPACE HEATING SYSTEMS

9.3.1 Conventional Resistance Space Heating Base System

The base is an electrical resistance duct heater. The electrical energy consumption of this system is equal to the heating load of the house. The annual energy consumption of this system is 46.9 GJ (13031 kWh). Of this total 25.4 GJ (7052 kWh) occurs during the on-peak period (8 am - 12 pm and 21.5 GJ (5979 kWh) occurs during the off-peak period. Table 9-1 lists the monthly electrical consumption of this system during the on- and off-peak peak periods. The average hourly consumption and peak load for each month are given in Table 9-2.

Table 9-1. Energy Consumed for Resistance Space Heating (kWh)
Columbus, Ohio

Month	On-Peak	Off-Peak	Total
January	1586	1239	2825
February	1489	1198	2687
March	928	873	1801
April	307	391	698
May	48	88	136
October	359	453	812
November	685	607	1292
December	1650	1130	2780
Annual Total	7052	5979	13031

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          AVERAGE DAILY PROFILE FOR 1964

         LOCATION: COLUMBUS OHIO

         ALL VALUES = KWH

         RESISTANCE HEATING


HOUR     JAN       FEB       MAR       APR       MAY       JUN       JUL       AUG       SEP       OCT       NOV       DEC

   1     4.508     4.759     2.763     0.876     0.102     0.080     0.000     0.000     0.211     0.840     1.589     4.298
   2     4.679     4.988     3.052     1.030     0.152     0.117     0.000     0.000     0.219     1.104     1.771     4.381
   3     4.809     5.142     3.315     1.230     0.189     0.132     0.000     0.000     0.266     1.460     2.035     4.440
   4     4.959     5.300     3.500     1.507     0.324     0.141     0.000     0.000     0.308     1.748     2.416     4.523
   5     5.100     5.452     3.615     1.721     0.446     0.148     0.000     0.023     0.345     1.904     2.776     4.602
   6     5.219     5.604     3.814     1.893     0.472     0.150     0.000     0.076     0.425     2.169     3.038     4.675
   7     5.309     5.732     4.006     2.217     0.530     0.188     0.000     0.177     0.581     2.496     3.195     4.738
   8     5.395     5.802     4.099     2.551     0.624     0.233     0.000     0.261     0.798     2.907     3.428     4.785
   9     5.473     5.846     4.086     2.467     0.605     0.229     0.000     0.239     0.924     3.363     3.766     4.815
  10     5.442     5.617     3.689     1.915     0.423     0.164     0.000     0.136     0.749     3.201     3.849     4.819
  11     4.916     4.950     2.921     1.223     0.213     0.072     0.000     0.034     0.352     2.136     3.233     4.548
  12     3.930     4.075     2.123     0.722     0.095     0.031     0.000     0.000     0.123     0.917     2.120     3.953
  13     3.011     3.161     1.459     0.455     0.041     0.026     0.000     0.000     0.080     0.218     1.246     3.317
  14     2.337     2.384     1.075     0.292     0.018     0.026     0.000     0.000     0.060     0.043     0.769     2.771
  15     1.880     1.891     0.927     0.165     0.022     0.024     0.000     0.000     0.052     0.041     0.500     2.398
  16     1.634     1.626     0.846     0.137     0.010     0.019     0.000     0.000     0.049     0.026     0.346     2.237
  17     1.528     1.534     0.832     0.161     0.000     0.016     0.000     0.000     0.047     0.030     0.304     2.225
  18     1.541     1.677     0.898     0.168     0.000     0.008     0.000     0.000     0.050     0.045     0.287     2.202
  19     1.994     1.997     1.060     0.215     0.000     0.000     0.000     0.000     0.049     0.074     0.462     2.528
  20     2.635     2.584     1.366     0.255     0.000     0.000     0.000     0.000     0.053     0.111     0.798     3.052
  21     3.117     3.282     1.751     0.342     0.000     0.000     0.000     0.000     0.063     0.174     0.999     3.387
  22     3.568     3.822     2.083     0.480     0.020     0.000     0.000     0.000     0.068     0.258     1.143     3.694
  23     3.943     4.226     2.306     0.585     0.044     0.000     0.000     0.000     0.103     0.365     1.381     3.925
  24     4.238     4.510     2.507     0.652     0.051     0.000     0.000     0.000     0.172     0.572     1.620     4.093
         PEAK HOURLY CONSUMPTION FOR EACH MONTH
MAX      9.553     7.464     6.839     6.311     3.561     2.395     0.000     3.011     3.694     5.542     7.042     7.911

DAY         14        23        18         1        29         3         3        15        13        11        22        18

HOUR        10         9         8         8         7         5         5         8         8         9         8        10

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9.3.2 Conventional Heat Pump

An outdoor evaporator coil extracts energy from the ambient air with an indoor condensing coil, located in the hot air duct, supplying energy to the heated space. For backup energy, a resistance heating coil is placed in the hot air duct downstream of the condenser coil to make up any portion of the heating load not met by the heat pump. Figure 4-10 shows a schematic representation of this system. The annual energy consumption of this system is 26.2 GJ (7275 kWh). The seasonal average coefficient of performance was 1.83. Of the total energy consumption, 13.8 GJ (3835 kWh) occurred during the on-peak periods and 12.4 GJ (3440 kWh) occurred during the off-peak periods. Table 9-3 lists the monthly electrical energy consumption of this system during the on- and off-peak periods. The average hourly consumption and peak load for each month are shown in Table 9-4.

Table 9-3. Energy Consumed by the Conventional Heat Pump for Space Heating (kWh), Columbus, Ohio

Month	On-Peak	Off-Peak	Total
January	910	751	1661
February	822	736	1558
March	472	473	945
April	154	206	360
May	23	44	67
October	182	230	412
November	364	337	701
December	908	662	1570
Annual Total	3835	3440	7275

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  AVERAGE DAILY PROFILE FOR 1964

 LOCATION: COLUMBUS OHIO

 ALL VALUES = KWH

 AIR TO AIR HEAT PUMP


HOUR    JAN      FEB      MAR      APR      MAY      JUN      JUL      AUG      SEP      OCT      NOV      DEC

  1    2.585    2.732    1.443    0.460    0.051    0.003    0.000    0.000    0.000    0.415    0.857    2.440
  2    2.724    2.935    1.621    0.546    0.076    0.000    0.000    0.000    0.000    0.545    0.970    2.519
  3    2.842    3.085    1.780    0.652    0.094    0.000    0.000    0.000    0.000    0.728    1.123    2.571
  4    2.982    3.235    1.893    0.792    0.161    0.000    0.000    0.000    0.000    0.880    1.331    2.644
  5    3.113    3.384    1.967    0.904    0.221    0.000    0.000    0.000    0.000    0.962    1.530    2.713
  6    3.224    3.535    2.082    0.996    0.234    0.000    0.000    0.000    0.000    1.108    1.686    2.773
  7    3.327    3.662    2.196    1.164    0.263    0.000    0.000    0.000    0.000    1.288    1.792    2.826
  8    3.432    3.731    2.266    1.338    0.309    0.000    0.000    0.000    0.000    1.509    1.930    2.873
  9    3.504    3.776    2.239    1.281    0.300    0.000    0.000    0.000    0.000    1.748    2.113    2.904
 10    3.480    3.550    1.936    0.975    0.210    0.000    0.000    0.000    0.000    1.624    2.149    2.907
 11    3.024    2.888    1.464    0.607    0.106    0.000    0.000    0.000    0.000    1.058    1.755    2.654
 12    2.240    2.174    1.046    0.357    0.047    0.000    0.000    0.000    0.000    0.455    1.099    2.180
 13    1.627    1.637    0.720    0.225    0.020    0.000    0.000    0.000    0.000    0.108    0.619    1.745
 14    1.253    1.212    0.530    0.145    0.009    0.000    0.000    0.000    0.000    0.021    0.379    1.405
 15    0.998    0.944    0.458    0.082    0.011    0.000    0.000    0.000    0.000    0.020    0.246    1.192
 16    0.876    0.808    0.417    0.068    0.005    0.000    0.000    0.000    0.000    0.013    0.171    1.113
 17    0.827    0.760    0.410    0.080    0.000    0.000    0.000    0.000    0.000    0.015    0.150    1.103
 18    0.837    0.833    0.443    0.083    0.000    0.000    0.000    0.000    0.000    0.022    0.142    1.091
 19    1.072    0.997    0.523    0.106    0.000    0.000    0.000    0.000    0.000    0.037    0.228    1.274
 20    1.412    1.305    0.674    0.126    0.000    0.000    0.000    0.000    0.000    0.055    0.394    1.574
 21    1.687    1.683    0.871    0.169    0.000    0.000    0.000    0.000    0.000    0.086    0.502    1.776
 22    1.953    1.999    1.047    0.237    0.010    0.000    0.000    0.000    0.000    0.128    0.594    1.973
 23    2.179    2.273    1.171    0.290    0.022    0.000    0.000    0.000    0.000    0.181    0.735    2.134
 24    2.384    2.512    1.294    0.328    0.026    0.000    0.000    0.000    0.000    0.282    0.878    2.261
        PEAK HOURLY CONSUMPTION FOR EACH MONTH
MAX    9.553    5.472    4.822    4.256    1.760    0.100    0.000    0.000    0.000    3.442    5.033    5.981

DAY       14       23       18        1       29        1        1        1        1       11       22       18

HOUR      10        9        8        8        7        1        1        1        1        9        8       10

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9.4 ENERGY ANALYSIS OF SOLAR SPACE HEATING SYSTEMS

9.4.1 Conventional Solar Space Heating System

The major components of this system are shown in Figure 4-4. The F-CHART computer program was used to compare the relationship between collector area and solar fraction in Philadelphia and Columbus. This comparison showed that a 15% greater collector area is required in Columbus to achieve the same solar fraction as a system in Philadelphia for solar fractions in the range of 40% to 50%. The collector areas for solar systems simulated using Columbus weather data were increased by 15% so that the Columbus and Philadelphia systems would achieve approximately the same solar fractions. The sizes of the collector pumps and solar storage tanks were also increased. Specifically, in the Columbus simulations a collector area of 48.3 m^2 (520 ft^2) a collector pump size of 187 watts (1/4 horsepower) and a solar storage tank size of 3.91 m^2 (1033 gallons) were used.

The monthly on- and off-peak performance as well as the monthly solar system performance is shown in Table 9-5. The average hourly profile by month for this system is shown in Table 9-6.

Table 9-5. Performance of Conventional Solar Heating System
Columbus, Ohio

Month	Auxiliary Energy Consumption			Solar[1] Fraction (%)	Solar System[2] Efficiency (%)
	On-Peak (kWh)	Off-Peak (kWh)	Total (kWh)		
January	1040	807	1847	35	23
February	978	742	1720	36	23
March	386	346	732	59	21
April	102	105	207	70	9
May	20	4	24	83	2
October	42	17	59	93	12
November	204	133	337	74	19
December	1508	995	2503	11	13
Annual Total	4280	3149	7429	44	9

[1] Solar Fraction $= \dfrac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$

[2] Solar System Efficiency $= \dfrac{\text{Solar Energy Delivered to Load}}{\text{Total Incident Energy on the Collectors}}$

Table 9-6. Average Hourly Profile for a Conventional Solar Heating System in Columbus, Ohio

AVERAGE DAILY PROFILE FOR 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

CONVENTIONAL SOLAR HEATING SYSTEM

SOLAR COLLECTOR AREA = 48.3 m^2 (520 ft^2)

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2.244	2.460	0.806	0.368	0.008	0.008	0.000	0.000	0.012	0.036	0.185	3.391
2	2.476	2.712	1.050	0.391	0.008	0.008	0.000	0.000	0.012	0.050	0.274	3.598
3	2.721	2.943	1.216	0.415	0.015	0.008	0.000	0.000	0.016	0.056	0.388	3.772
4	2.991	3.143	1.404	0.430	0.020	0.008	0.000	0.000	0.017	0.060	0.452	3.914
5	3.414	3.360	1.570	0.444	0.020	0.008	0.000	0.000	0.020	0.064	0.522	4.108
6	3.782	3.682	1.665	0.470	0.020	0.008	0.000	0.000	0.021	0.075	0.699	4.243
7	4.074	3.920	1.715	0.486	0.024	0.012	0.000	0.000	0.035	0.090	0.885	4.439
8	4.320	4.269	1.745	0.502	0.031	0.016	0.000	0.000	0.045	0.110	1.016	4.644
9	4.473	4.621	1.785	0.488	0.036	0.017	0.000	0.000	0.049	0.119	1.192	4.756
10	4.492	4.625	1.707	0.433	0.040	0.017	0.000	0.000	0.050	0.120	1.365	4.800
11	4.066	4.235	1.434	0.375	0.038	0.018	0.000	0.000	0.046	0.120	1.332	4.545
12	3.197	3.272	0.952	0.219	0.039	0.032	0.010	0.006	0.023	0.128	1.053	3.957
13	1.868	2.173	0.650	0.202	0.084	0.087	0.076	0.068	0.051	0.157	0.523	3.215
14	1.369	1.572	0.574	0.190	0.095	0.110	0.093	0.107	0.094	0.144	0.285	2.589
15	1.217	1.331	0.506	0.167	0.099	0.119	0.111	0.114	0.098	0.145	0.203	2.151
16	1.112	1.184	0.466	0.158	0.097	0.114	0.107	0.110	0.099	0.128	0.158	1.994
17	1.125	1.108	0.441	0.167	0.063	0.085	0.063	0.074	0.087	0.105	0.155	1.965
18	1.147	1.128	0.451	0.143	0.015	0.015	0.004	0.003	0.020	0.082	0.144	1.947
19	1.188	1.184	0.468	0.110	0.000	0.000	0.000	0.000	0.005	0.020	0.061	2.155
20	1.338	1.302	0.504	0.115	0.000	0.000	0.000	0.000	0.004	0.012	0.037	2.533
21	1.488	1.517	0.559	0.136	0.000	0.000	0.000	0.000	0.004	0.012	0.041	2.735
22	1.621	1.679	0.593	0.155	0.004	0.000	0.000	0.000	0.004	0.016	0.045	2.908
23	1.821	1.862	0.628	0.167	0.004	0.000	0.000	0.000	0.008	0.023	0.079	3.122
24	2.043	2.144	0.720	0.180	0.008	0.000	0.000	0.000	0.012	0.031	0.147	3.264
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	9.553	7.464	6.083	6.311	0.168	0.168	0.168	0.168	0.214	0.276	7.042	7.911
DAY	14	23	30	1	1	3	3	1	30	10	22	18
HOUR	10	9	8	8	12	12	14	15	12	14	8	10

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9.4.2 Solar Space Heating System with Separate Off-Peak Storage

A diagram of this system is shown as Figure 4-8. The off-peak storage tank is charged with electrical energy during the period 12 midnight to 8 am. The off-peak storage tank has a volume of 2.86 m^3 (750 gallons).

The monthly on- and off-peak performance as well as the monthly solar system performance is shown in Table 9-7. The average hourly profile by month for this system is shown in Table 9-8.

Table 9-7. Performance of Solar Space Heating System with Separate Off-Peak Storage in Columbus, Ohio

	Auxiliary Energy Consumption				
Month	On-Peak (kWh)	Off-Peak (kWh)	Total (kWh)	Solar[1] Fraction (%)	Solar System[2] Efficiency (%)
January	73	2645	2718	4	18
February	67	2379	2446	9	19
March	61	1206	1267	30	19
April	38	467	505	28	9
May	20	301	321	-136	2
October	42	442	484	40	12
November	52	784	836	35	17
December	67	3102	3169	-13	8
Annual Total	420	11,326	11,746	10	8

[1] Solar Fraction = $\frac{\text{Total Load - Auxiliary Energy}}{\text{Total Load}}$

[2] Solar System Efficiency = $\frac{\text{Solar Energy Delivered to Load}}{\text{Total Incident Energy on the Collectors}}$

9.4.3 Solar Assisted Dual Source Heat Pump with Direct Heating from Solar

A diagram of this system is shown as Figure 4-18. When the solar storage temperature is greater than 35°C (95°F) space heating is supplied directly from solar storage. When solar storage has a temperature less than 35°C (95°F) space heating is provided by the heat pump using solar storage as a source. If solar storage is depleted, the heat pump uses ambient air as a source.

Table 9-8. Average Hourly Profile for a Solar Heating System With Separate Off-Peak Storage in Columbus, Ohio

AVERAGE DAILY PROFILE FOR 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SOLAR HEATING WITH SEPERATE OFF-PEAK STORAGE

SOLAR COLLECTOR AREA = 48.3 m^2 (520 ft^2)

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
2	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
3	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
4	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
5	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
6	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
7	10.745	10.598	4.828	1.998	1.232	0.134	0.000	0.000	1.554	1.785	3.212	12.560
8	0.124	0.124	0.124	0.112	0.048	0.017	0.000	0.000	0.062	0.112	0.116	0.124
9	0.124	0.124	0.124	0.112	0.036	0.017	0.000	0.000	0.050	0.120	0.120	0.124
10	0.124	0.124	0.124	0.104	0.040	0.017	0.000	0.000	0.050	0.120	0.124	0.124
11	0.124	0.124	0.173	0.114	0.021	0.019	0.000	0.000	0.021	0.116	0.124	0.124
12	0.211	0.190	0.191	0.131	0.066	0.049	0.038	0.038	0.019	0.125	0.123	0.141
13	0.207	0.214	0.163	0.114	0.090	0.110	0.092	0.097	0.092	0.140	0.164	0.158
14	0.192	0.205	0.153	0.121	0.101	0.110	0.108	0.108	0.093	0.147	0.159	0.170
15	0.199	0.193	0.145	0.096	0.101	0.127	0.108	0.113	0.105	0.138	0.149	0.168
16	0.184	0.197	0.141	0.091	0.086	0.105	0.103	0.097	0.093	0.116	0.155	0.153
17	0.180	0.179	0.125	0.106	0.043	0.038	0.022	0.022	0.054	0.089	0.145	0.140
18	0.169	0.161	0.114	0.050	0.000	0.000	0.000	0.000	0.010	0.067	0.125	0.140
19	0.092	0.093	0.064	0.017	0.000	0.000	0.000	0.000	0.004	0.008	0.037	0.104
20	0.096	0.107	0.076	0.017	0.000	0.000	0.000	0.000	0.004	0.012	0.037	0.112
21	0.108	0.111	0.084	0.025	0.000	0.000	0.000	0.000	0.004	0.012	0.041	0.120
22	0.112	0.120	0.084	0.029	0.004	0.000	0.000	0.000	0.004	0.016	0.046	0.120
23	0.120	0.120	0.084	0.029	0.004	0.000	0.000	0.000	0.008	0.024	0.054	0.124
24	10.095	10.782	5.112	1.578	1.083	0.130	0.000	0.000	1.565	1.775	3.648	12.141
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	25.428	21.889	17.336	17.336	5.881	3.642	0.168	0.168	15.436	7.461	17.442	28.806
DAY	13	7	31	1	27	2	2	1	7	19	20	17
HOUR	24	24	24	1	24	24	13	14	24	24	24	24

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The monthly on- and off-peak performance as well as the monthly solar system performance is shown in Table 9-9. The average hourly profile by month for this system is shown in Table 9-10.

Table 9-9. Performance of a Solar Assisted Dual Source Heat Pump With Direct Heating from Solar in Columbus, Ohio

Month	Auxiliary Energy Consumption On-Peak (kWh)	Auxiliary Energy Consumption Off-Peak (kWh)	Auxiliary Energy Consumption Total (kWh)	Solar[1] Fraction (%)	Solar System[2] Efficiency (%)
January	660	454	1114	61	36
February	566	434	1000	63	34
March	196	158	354	80	27
April	68	57	125	82	9
May	14	0	14	90	1
October	21	0	21	97	11
November	107	72	179	86	20
December	792	558	1350	52	31
Annual Total	2424	1733	4157	68	12

[1] $\text{Solar Fraction} = \dfrac{\text{Total Load-Auxiliary Energy}}{\text{Total Load}}$

[2] $\text{Solar System Efficiency} = \dfrac{\text{Usable Energy from Solar Storage}}{\text{Total Incident Energy on Collectors}}$

9.5 ENERGY ANALYSIS OF SPACE COOLING SYSTEMS

The performance of three solar air conditioning (A/C) systems was compared with that of a conventional vapor compression unit. Cooling loads were calculated for the typical house described in Subsection 9.1 using weather data from 1964 for Columbus, Ohio. The solar cooling systems analyzed included a conventional solar air conditioner and two solar A/C with different off-peak hot storage capacities. A schematic diagram of a conventional solar air conditioner is shown in Figure 4-24 and a diagram of a solar air conditioner with off-peak hot storage is shown in Figure 4-26. In both diagrams, the cooling tower is not shown. The operation of these systems is discussed in Appendix B.

Table 9-10. Average Hourly Profile for a Solar Assisted Dual Source Heat Pump With Direct Heating from Solar in Columbus, Ohio

AVERAGE DAILY PROFILE FOR 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SOLAR ASSISTED DUAL SOURCE HEAT PUMP
WITH DIRECT HEATING FROM SOLAR

SOLAR COLLECTOR AREA = 48.3 m^2 (520 ft^2)

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	1.547	1.409	0.509	0.144	0.000	0.000	0.000	0.000	0.000	0.000	0.199	2.005
2	1.606	1.553	0.570	0.157	0.000	0.000	0.000	0.000	0.000	0.000	0.231	2.063
3	1.660	1.787	0.616	0.168	0.000	0.000	0.000	0.000	0.000	0.000	0.240	2.147
4	1.763	1.866	0.636	0.190	0.000	0.000	0.000	0.000	0.000	0.000	0.260	2.254
5	1.826	2.073	0.654	0.273	0.000	0.000	0.000	0.000	0.000	0.000	0.287	2.312
6	1.890	2.152	0.694	0.290	0.000	0.000	0.000	0.000	0.000	0.000	0.355	2.367
7	2.045	2.276	0.706	0.328	0.000	0.000	0.000	0.000	0.000	0.000	0.383	2.405
8	2.313	2.391	0.717	0.357	0.000	0.000	0.000	0.000	0.000	0.000	0.439	2.436
9	2.439	2.493	0.712	0.344	0.000	0.000	0.000	0.000	0.000	0.000	0.492	2.459
10	2.458	2.493	0.676	0.287	0.000	0.000	0.000	0.000	0.000	0.000	0.523	2.456
11	2.240	2.120	0.567	0.221	0.001	0.001	0.000	0.000	0.000	0.000	0.476	2.261
12	1.725	1.734	0.450	0.208	0.018	0.024	0.010	0.006	0.004	0.015	0.410	1.914
13	1.262	1.349	0.342	0.186	0.069	0.082	0.076	0.068	0.040	0.101	0.333	1.538
14	1.012	1.023	0.291	0.156	0.091	0.106	0.093	0.107	0.086	0.128	0.265	1.265
15	0.849	0.819	0.268	0.131	0.093	0.112	0.111	0.114	0.094	0.133	0.201	1.109
16	0.759	0.703	0.254	0.127	0.091	0.107	0.107	0.110	0.096	0.118	0.156	1.019
17	0.720	0.665	0.246	0.124	0.062	0.080	0.063	0.074	0.082	0.095	0.140	1.012
18	0.720	0.674	0.249	0.100	0.012	0.010	0.004	0.003	0.014	0.074	0.113	1.038
19	0.809	0.736	0.268	0.062	0.000	0.000	0.000	0.000	0.001	0.008	0.029	1.147
20	0.979	0.816	0.288	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.381
21	1.090	0.989	0.341	0.057	0.000	0.000	0.000	0.000	0.000	0.000	0.021	1.541
22	1.295	1.131	0.403	0.064	0.000	0.000	0.000	0.000	0.000	0.000	0.091	1.690
23	1.411	1.201	0.458	0.069	0.000	0.000	0.000	0.000	0.000	0.000	0.157	1.816
24	1.512	1.265	0.490	0.074	0.000	0.000	0.000	0.000	0.000	0.000	0.176	1.919
	PEAK HOURLY CONSUMPTION FOR EACH MONTH											
MAX	9.553	5.472	2.889	4.256	0.168	0.168	0.168	0.168	0.168	0.168	2.519	5.981
DAY	14	23	11	1	1	3	3	1	2	1	22	18
HOUR	10	9	8	8	12	12	14	15	16	13	8	10

In each case, the solar A/C were simulated with a collector area of $55.8\ m^2$ ($600\ ft^2$) and solar storage of a capacity equivalent to $81.5\ kg/m^2$ ($2\ gal/ft^2$) of collector area. The two solar A/C with off-peak hot storage had off-peak storage capacities of $2\ m^3$ (530 gallons) and $3\ m^3$ (790 gallons), respectively.

Simulation Results

Monthly energy usage for the conventional compression air conditioning system and the three solar air conditioning systems is shown in Table 9-11. It can be seen that the solar A/C use significantly more electrical energy during the cooling season than the conventional system; however, the solar A/C with off-peak storage reduces on-peak energy usage. The solar A/C with the $2\ m^2$ of off-peak hot storage has the lowest on-peak energy usage. It also has a lower seasonal energy usage than the system with $3\ m^2$ of off-peak hot storage. However, while the system with the smaller off-peak hot storage has a lower system cost and seasonal energy usage than the system with the larger off-peak hot storage, the smaller system is unable to supply 3% of the seasonal load whereas the large system is able to meet all but 0.4% of the seasonal load. Thus the savings in system cost and energy usage achievabl with a smaller off-peak storage would be at the expense of the system owner's comfort.

Table 9-11. Air Conditioning System Monthly Energy Usage (kWh)
Columbus, Ohio

Month	Compression A/C		Conventional Solar A/C with $55.8\ m^2$ of Collector Area		Solar A/C With $55.8\ m^2$ Collector Area and $2\ m^3$ Off-Peak Storage		Solar A/C With $55.8\ m^2$ Collector Area and $3\ m^3$ Off-Peak Storage	
	On Peak	Off Peak	On Peak	Off Peak	On Peak	Off Peak	On Peak	Off Peak
May	251	7	259	29	144	246	148	271
June	433	39	665	171	169	624	179	704
July	555	54	947	274	209	1100	220	1171
August	449	35	759	160	183	720	194	819
September	275	8	273	30	136	255	141	277
Total	1963	143	2903	664	841	2946	882	3242
	2106		3567		3787		4124	

The monthly peak electric demands are shown in Table 9-12. The magnitudes of the demands and the day and hour when they occur are given. It can be seen that during all months the conventional solar A/C will have higher peak demands than the compression A/C. The peaks for either system generally occur during the afternoon and evening hours. By charging an off-peak storage tank, the system peaks are shifted to the early morning hours, and the maximum demand during the on-peak period is reduced by at least a factor of 4 as compared to the compression A/C system. During the day, the off-peak systems only use energy to run pumps and fans.

Table 9-12. Air Conditioning System Monthly Peak Demands (kW)
Columbus, Ohio

	Compression A/C			Conventional Solar A/C			Solar A/C with 2 m^3 Off-Peak Storage	Solar A/C with 3 m^3 Off-Peak Storage
Month	Day	Hour	Demand	Day	Hour	Demand	Demand*	Demand*
May	19	15	2.10	8	18	5.55	7.88	10.1
June	23	15	2.43	19	19	9.28	7.88	10.1
July	27	15	2.35	25	18	9.23	7.88	10.1
August	2	16	2.73	2	18	10.37	7.88	10.1
September	10	16	2.79	10	12	5.92	7.88	10.1

*These demands occur between the hours of midnight and 8 AM when the off-peak storage is being heated with electrical energy. When the off-peak storage is not being charged, the maximum demand is ≈0.5 kW.

System daily demand profiles averaged for each month are shown in Tables 9-13 through 9-16. That is, for a given month and hour, the demand shown is the average of all the demands for that hour during the month.

The performance of the solar components for each solar air conditioning system is shown in Table 9-17.

Table 9-13. Average Hourly Profile for Conventional Air Conditioning in Columbus, Ohio

AIR CONDITIONING AVERAGE DAILY PROFILES FOR MAY THRU SEPTEMBER 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SYSTEM = CONVENTIONAL COMPRESSION AIR CONDITIONER

HOUR	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1	0.095	0.302	0.416	0.286	0.122
2	0.055	0.224	0.312	0.207	0.069
3	0.030	0.165	0.231	0.148	0.032
4	0.015	0.122	0.170	0.111	0.014
5	0.009	0.089	0.123	0.088	0.005
6	0.008	0.085	0.095	0.070	0.002
7	0.009	0.117	0.134	0.076	0.002
8	0.016	0.203	0.255	0.134	0.005
9	0.060	0.340	0.432	0.230	0.018
10	0.131	0.502	0.658	0.366	0.089
11	0.198	0.672	0.903	0.571	0.234
12	0.316	0.840	1.125	0.800	0.432
13	0.499	0.980	1.330	1.011	0.628
14	0.661	1.092	1.492	1.222	0.796
15	0.749	1.170	1.549	1.381	0.950
16	0.795	1.217	1.537	1.430	1.038
17	0.834	1.244	1.526	1.422	1.039
18	0.863	1.270	1.530	1.401	0.990
19	0.831	1.266	1.459	1.270	0.868
20	0.711	1.123	1.266	1.031	0.688
21	0.550	0.910	1.028	0.810	0.515
22	0.409	0.740	0.837	0.645	0.390
23	0.292	0.601	0.703	0.522	0.301
24	0.179	0.453	0.549	0.397	0.205

Table 9-14. Average Hourly Profile for Conventional Solar Air Conditioning with 55.8 m^2 Collector Area in Columbus, Ohio

AIR CONDITIONING AVERAGE DAILY PROFILES FOR MAY THRU SEPTEMBER 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SYSTEM = CONVENTIONAL SOLAR AIR CONDITIONER

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1	0.265	1.166	1.898	1.013	0.361
2	0.169	0.759	1.579	0.859	0.198
3	0.132	0.642	0.990	0.751	0.178
4	0.105	0.614	0.788	0.625	0.101
5	0.062	0.461	0.688	0.472	0.069
6	0.050	0.484	0.595	0.401	0.022
7	0.056	0.628	0.844	0.412	0.023
8	0.097	0.935	1.456	0.629	0.034
9	0.116	1.395	2.282	1.119	0.128
10	0.195	1.518	2.777	1.416	0.420
11	0.221	1.294	1.185	1.187	0.463
12	0.315	1.060	1.388	1.355	0.710
13	0.380	1.125	1.240	1.479	0.564
14	0.427	1.232	1.227	1.553	0.588
15	0.722	1.593	1.327	1.491	0.678
16	0.704	1.510	1.138	1.434	0.699
17	0.711	1.527	1.777	2.319	0.686
18	0.742	1.781	2.754	2.658	0.754
19	0.780	2.065	3.404	1.917	0.720
20	0.746	1.294	1.735	1.199	0.705
21	0.700	0.931	1.664	1.175	0.560
22	0.649	1.217	2.023	1.398	0.544
23	0.536	1.319	2.613	1.536	0.471
24	0.409	1.326	2.022	1.235	0.429

Table 9-15. Average Hourly Profile for Solar Air Conditioning with 55.8 m^2 Collector Area and 2 m^3 Off-Peak Hot Storage in Columbus, Ohio

AIR CONDITIONING AVERAGE DAILY PROFILES FOR MAY THRU SEPTEMBER 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SYSTEM = SOLAR AIR CONDITIONER WITH OFF PEAK HOT WATER STORAGE

OFF PEAK STORAGE VOLUME = 2 m^3 (530 gallons)

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1	0.991	2.605	4.436	2.904	1.061
2	0.991	2.605	4.436	2.904	1.061
3	0.991	2.605	4.436	2.904	1.061
4	0.991	2.605	4.436	2.904	1.061
5	0.991	2.605	4.436	2.904	1.061
6	0.991	2.605	4.436	2.904	1.061
7	0.991	2.605	4.436	2.904	1.061
8	0.991	2.605	4.436	2.904	1.061
9	0.082	0.221	0.320	0.168	0.050
10	0.147	0.293	0.401	0.267	0.136
11	0.168	0.316	0.418	0.323	0.209
12	0.240	0.330	0.451	0.353	0.244
13	0.270	0.348	0.466	0.380	0.258
14	0.292	0.368	0.467	0.424	0.295
15	0.329	0.380	0.462	0.416	0.319
16	0.317	0.372	0.444	0.399	0.298
17	0.294	0.335	0.390	0.372	0.280
18	0.305	0.329	0.380	0.367	0.302
19	0.305	0.329	0.376	0.367	0.316
20	0.305	0.319	0.367	0.355	0.316
21	0.305	0.323	0.354	0.341	0.315
22	0.293	0.324	0.330	0.321	0.288
23	0.280	0.299	0.320	0.305	0.239
24	0.711	0.747	0.789	0.739	0.682

Table 9-16. Average Hourly Profile for Solar Air Conditioning with 55.8 m^2 Collector Area and 3 m^3 Off-Peak Hot Storage in Columbus, Ohio

AIR CONDITIONING AVERAGE DAILY PROFILES FOR MAY THRU SEPTEMBER 1964

LOCATION: COLUMBUS OHIO

ALL VALUES = KWH

SYSTEM = SOLAR AIR CONDITIONER WITH OFF PEAK HOT WATER STORAGE

OFF PEAK STORAGE VOLUME = 3 m^3 (790 gallons)

SOLAR COLLECTOR AREA = 55.8 m^2 (600 ft^2)

HOUR	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1	1.091	2.934	4.723	3.301	1.155
2	1.091	2.934	4.723	3.301	1.155
3	1.091	2.934	4.723	3.301	1.155
4	1.091	2.934	4.723	3.301	1.155
5	1.091	2.934	4.723	3.301	1.155
6	1.091	2.934	4.723	3.301	1.155
7	1.091	2.934	4.723	3.301	1.155
8	1.091	2.934	4.723	3.301	1.155
9	0.082	0.221	0.320	0.168	0.050
10	0.147	0.293	0.401	0.267	0.136
11	0.168	0.316	0.418	0.323	0.209
12	0.240	0.330	0.451	0.353	0.244
13	0.270	0.348	0.466	0.380	0.258
14	0.292	0.368	0.467	0.431	0.295
15	0.329	0.384	0.462	0.429	0.319
16	0.317	0.384	0.445	0.412	0.298
17	0.294	0.348	0.390	0.384	0.280
18	0.305	0.342	0.380	0.380	0.302
19	0.305	0.341	0.380	0.380	0.316
20	0.305	0.331	0.380	0.380	0.316
21	0.305	0.343	0.380	0.367	0.315
22	0.293	0.347	0.380	0.344	0.288
23	0.280	0.341	0.380	0.330	0.239
24	0.859	0.934	0.986	0.931	0.821

Table 9-17. Performance of Solar Air Conditioning System Solar Components

	Conventional Solar A/C With 55.8 m^2 of Collector Area		Solar A/C With 2 m^2 Off-Peak Hot Storage		Solar A/C With 3 m^3 Off-Peak Hot Storage	
	GJ	Btu x 10^6	GJ	Btu x 10^6	GJ	Btu x 10^6
Solar Radiation Incident on Collectors	163	154.6	163	154.6	163	154.6
Energy Collected and Delivered to Storage	26.6	25.2	26.6	25.2	26.6	25.2
Collector Efficiency	16.3%		16.3%		16.3%	
Energy Lost From Solar Storage	2.0	1.9	2.1	2.0	2.1	2.0
Solar Storage Efficiency	92.5%		92.1%		92.1%	
Auxiliary Energy Input to Off-Peak Storage			10.2	9.7	11.3	10.7
Energy Lost From Off-Peak Storage			1.5	1.4	2.0	1.9
Off-Peak Storage Efficiency			85.3%		82.3%	

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 RECAPITULATION

The effects of using all-electric water heating and space conditioning systems with and without solar assistance and with and without off-peak storage were evaluated. Energy consumption, peak electrical loads, utility costs to serve, and homeowner capital costs were determined in various locations of the country for summer peaking and winter peaking utilities having different generation and demand patterns. Systems were rated based on total costs: utility cost to serve plus the homeowner's cost to install the system assuming it is financed by a 12% mortgage amortizable over 20 years. Electric tariffs were not considered since they are costs internal to the "utility plus homeowner" system, and it was desired to determine what systems would be best for society as a whole. Tax considerations were not considered for the same reasons.

Costs were determined for the years 1985 and 1995 in order to identify trends. Utility costs were obtained from the cooperating utilities or, where these costs were not available, they were calculated using published financial data. Equipment costs were obtained from manufacturers and from published estimating manuals. A summary of major findings is presented in Table 10-1. Results for specific locations are given on pages 6-4 through 6-6, 7-26 through 7-29, and 8-26 through 8-29.

10.2 CONCLUSIONS

1. The use of off-peak storage in residential space conditioning systems is effective in reducing on-peak demands of those homes to nominal values which are required to power pumps and fans. Table 10-2 shows the energy performance of a large number of such systems for Philadelphia, PA.
2. The technology exists for the large-scale application of off-peak storage exists. Both storage devices and controllers are commercially available.

Table 10-1. Relative Effects of Adding Different Systems Components on Energy Consumption and Costs, Calculated at Three U.S. Locations

Comparison	Item	Percentage Changes** at: Philadelphia, PA	Daytona Beach, FL	San Diego, CA
Adding off-peak storage to electric water heating	Energy Consumption	+	+5	
	Cost to serve	-	-64/-55	
	Total cost	±0	-50±	
Adding off-peak storage to solar water heating	Energy Consumption		+9	
	Cost to serve		-62/-43	
	Total cost		-16	
Adding off-peak storage to electric resistance space heating	Energy Consumption	+16	+9	+10
	Cost to serve	-	-49	-50
	Total cost	+	-13/-24	+12/0
Solar heating compared to resistance heating	Energy Consumption	-42	-14	-61*
	Cost to serve	-17	-7	-43*
	Total cost	+115	+39/+24	+28/+14*
Adding off-peak storage to solar heating	Energy Consumption	+27	+9	+10*
	Cost to serve	-20/-24	-50	-50*
	Total cost	+11/+8	-13/-24	±0 *
Solar heating & A/C compared to electrical heating & A/C	Energy Consumption	-34	+95	-70
	Cost to serve	+34/+19	-4	-75
	Total cost	+300/+260	+210/+150	+220/+170
Adding hot off-peak storage to solar heating & A/C	Energy Consumption	+21	+5	+53
	Cost to serve	-65	-33	-3
	Total cost	-8/-13	±0	+19

---

* These values include solar water and space heating.

** Where two values are shown separated by a slash (/), the first value pertains to 1985, the second to 1995. Where only a single value is shown, the percentage changes for 1985 and 1995 are the same or differ only slightly.

Where no numerical value is given with the + or - signs, the changes are small.

Table 10-2. Annual Performance of Selected Space Heating Systems in Philadelphia, PA

SYSTEM	TOTAL ANNUAL ELECTRICAL ENERGY CONSUMPTION (GJ)	ELECTRICAL DEMAND AT UTILITY RESIDENTIAL LOAD PEAK (kW)	REDUCTION IN PEAK COMPARED TO RESISTANCE (%)	ENERGY PENALTY COMPARED TO NO OFF-PEAK STORAGE (%)
Resistance Heating	64	9.16	Base	Base
Resistance w/Off-Peak Storage	74	0.63	99	16
Conventional Solar	37	9.16	0	Base
Solar w/Off-Peak in Solar Storage Tank	77	0.63	99	108
Solar w/Separate Off-Peak Storage (2 Tanks)	47	0.63	99	27
Conventional Air to Air Heat Pump	27	7.19	23	Base
Heat Pump w/Off-Peak Storage	41	4.28	56	52
Solar Assisted Heat Pump	33	9.16	0	22
Solar Assisted Heat Pump w/Off-Peak in Solar Storage Tank	40	3.92	61	48
Solar Assisted Dual Source Heat Pump w/Direct Heating from Solar	20	7.19	23	Base
Solar Assisted Dual Source Heat Pump w/Direct Heating and Off-Peak in Solar Storage Tank	24	4.27	56	20
Solar Assisted Dual Source Heat Pump w/Direct Heating and Separate Off-Peak Tank (2 Tanks)	25	3.56	65	25

3. The combination of solar space conditioning with utility load management through thermal storage is beneficial in many cases. The best method of accomplishing load management is through a separate storage device which is electrically charged during off-peak hours. Combining solar storage and off-peak storage in a single container is practical in highly stratified storage devices only, such as tall cylindrical water tanks or well-designed rock beds.

4. The air-to-air heat pump is the most economical of all space heating and cooling systems investigated. Although it was analyzed in one location only, this conclusion is believed to be valid throughout the country. A different conclusion may be reached if heating-only systems are compared. This was not done in the present study.

5. The addition of off-peak storage to an electric water heating system is justified when the cost differential between on-peak and off-peak electric energy is greater than approximately 0.5 ¢/kWh. It increases energy consumption by less than 10% but significantly reduces the utility cost-to-serve. On the other hand, the homeowner must install a larger water heater.

6. Adding off-peak (electrical) storage to a solar water heater decreases utility cost and decreases total cost. The addition of off-peak storage in a separate tank requires a significant cost increase, but the utility's cost to serve is also reduced considerably. Although this analysis was performed for a single utility only, cost and performance comparisons show that this conclusion may be generally valid.

7. The addition of off-peak storage to an electric resistance space heating system increases total energy consumption on the order of 10% to 20%, it may cut the utility cost to serve by as much as one-half, but it does not result in an overall cost saving at all locations investigated. At the most favorable location (Daytona Beach) this system is less costly, at San Diego it is more costly until shortly after 1995 when it begins to break even, and at Philadelphia it has no effect on total costs.

8. The cost comparison between electric heating and solar heating backed up by electric resistance heating is extremely climate dependent and depends less on utility costs. At no location is solar heating cost competitive with conventional heating, nor will it become so through the end of the century, unless electric energy costs change drastically.

9. Solar heating systems save 50% to 80% of electrical energy depending on design. The cost to serve such solar systems is less than the cost to serve conventional resistance heating systems at all locations studied. However, the high capital cost of the solar systems makes their total cost higher than that of electric resistance systems.

10. The addition of off-peak storage to a solar space heating system increases energy consumption between 9% and 27% at the locations studied. The increase is higher at less favorable solar locations. The cost to serve those systems is reduced everywhere when off-peak storage is added. However, the overall costs show an increase at one location, a decrease at another, and no change at a third. The advisability of adding off-peak storage to solar heating systems must, therefore, be investigated in each individual case, taking proper account of climate and utility costs.

11. Solar assisted heat pumps have lower back-up energy consumption and lower costs to serve but higher total costs than solar space heating systems with electric resistance back-up.

12. The addition of off-peak storage to solar assisted or conventional heat pumps does not result in an overall cost reduction.

13. Solar heating combined with solar absorption air conditioning is not competitive with conventional electric heating and air conditioning anywhere in the country. While energy savings are achieved, utility costs are higher everywhere, even for the winter peaking utility studied. Total costs for solar heating/cooling systems are approximately 3 to 4 times the costs of conventional systems in 1985, and 2.5 to 3.5 times conventional costs in 1995. Unless a different method of solar air conditioning can be developed, solar air conditioning with electric back-up is not likely to become commercial in this century.

14. The addition of off-peak storage to solar heating/cooling systems increases energy consumption by 20% to 35%, and decreases the cost to serve considerably. Overall costs are decreased in unfavorable solar climates (8% to 13% in Philadelphia) and are increased in favorable climates (19% in San Diego).

15. Hot storage in solar air conditioning systems is somewhat more favorable than cold storage.

16. The presence of a solar heating system on an electric utility network decreases its fuel cost. Calculated on a *marginal* cost basis, this annual cost avoidance amounts to $550 per solar heating customer in Philadelphia for Philadelphia Electric Company in 1985, and it increases with time. Under present tariffs, this cost avoidance is beneficial to *all* customers of that utility, because it results in a decrease in their fuel charges of less than 0.01 ¢/kWh. However, the benefits of this cost avoidance do not accrue to the homeowner who has made an investment in a solar system. This could provide a rationale for so-called subsidies of solar systems.

10.3 RECOMMENDATIONS

1. Investigate the accuracy of temperature predictions for the following day based on the previous evening's weather forecast. The potential savings that can be obtained from off-peak storage depend to a large degree on good weather predictions. No comprehensive data on the accuracy of those predictions appear to exist.
2. Investigate whether the use of gas as a back-up energy source could be more advantageous than the use of electric energy investigated in this report.
3. Continue the development of other than solar absorption air conditioning systems that have a promise of lower first cost.
4. Perform an investigation to determine the interface between passive solar heated and cooled buildings and electric utilities.
5. Determine the electric tariffs that will be required to induce homeowners to install solar and off-peak storage systems in a manner that is advantageous to both the homeowner and the electric utility.
6. Continue the investigations into methods of marginal cost pricing for solar heating customers of electric utilities.

7. Determine what subsidies or introductory tariffs electric utilities could offer to homeowners willing to install solar and/or off-peak storage systems.

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APPENDIX A

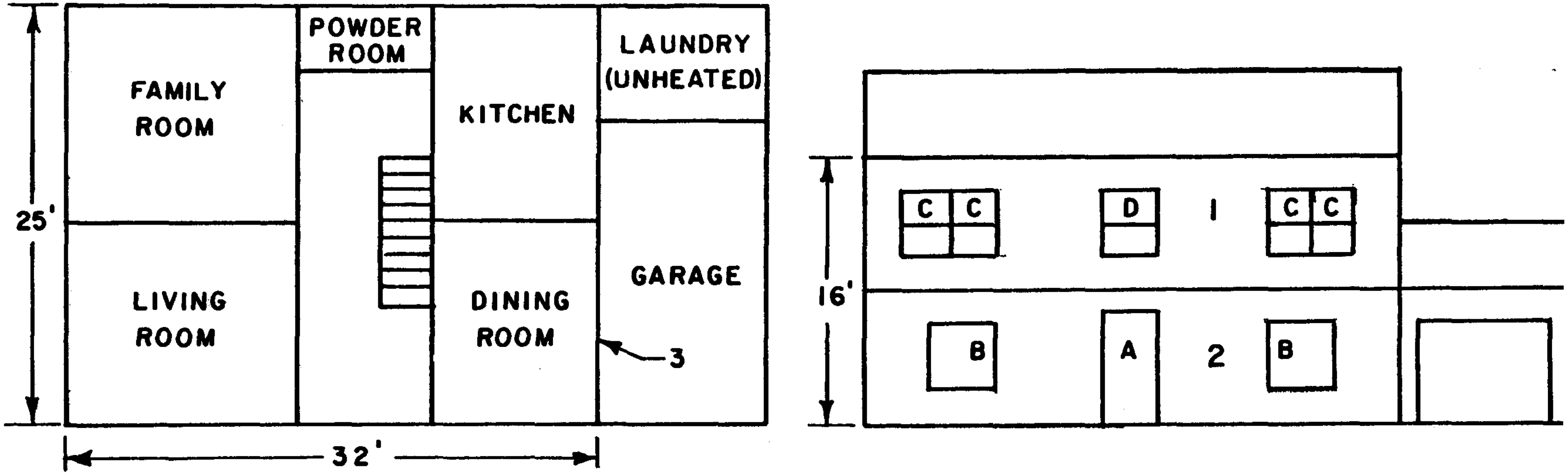
ENERGY CONSUMPTION OF A TYPICAL HOME

The typical home within the Philadelphia Electric Company (PECo) service territory is a single-family dwelling located in the suburbs of Philadelphia. Currently, 88% of residential construction with the PECo service territory takes place outside of the city of Philadelphia. The "typical" home used throughout this report is representative of the homes now being built or planned to be built within the next five years. This home was developed from discussions with the Philadelphia Home Builders Association and five of the larger home builders in the area.

A.1 TYPICAL HOME

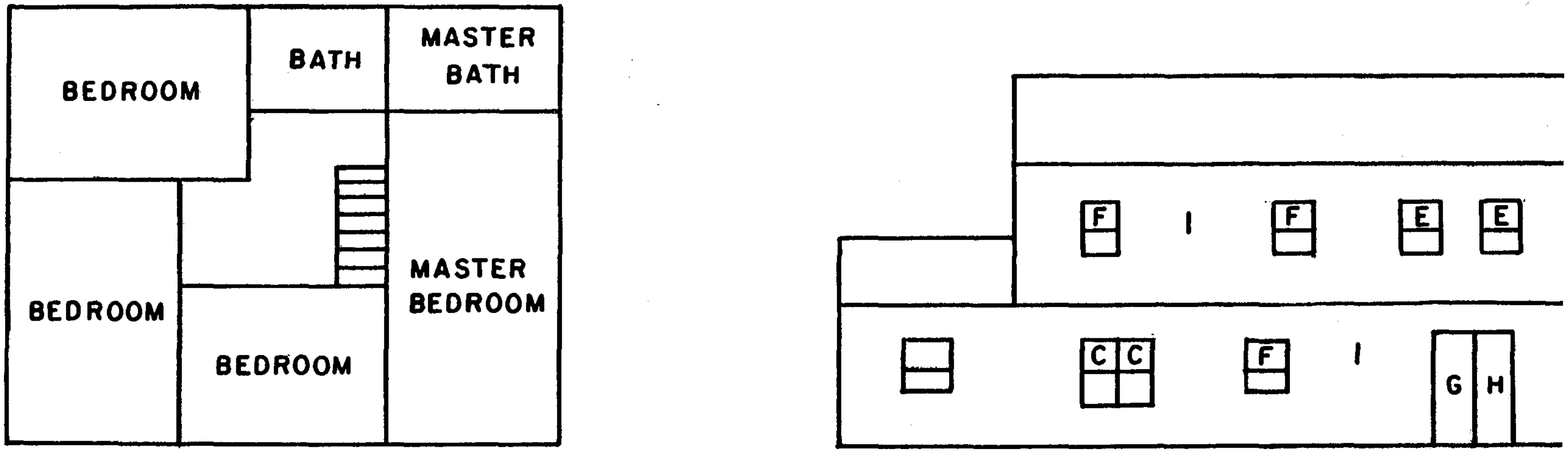
The typical home is a two-story frame structure with 148.6 square meters (1600 ft^2) of floor area, and unheated basement, and an attached garage. The house is insulated with 22 cm (9 inches) of fiberglass in the ceiling, 10 cm (4 inches) of fiberglass in the floor, and 9 cm (3-1/2 inches) of fiberglass plus 2.5 cm (1 inch) of styrofoam in the walls.

This typical home (see Figures A-1 and A-2) has a south-facing roof, four bedrooms, and is occupied by four people. The total floor area does not include the area of the basement or attached garage. The home has a floor to ceiling height of 2.44 m (8 ft), a total ceiling area of 74.3 m^2 (800 ft^2) which does not include the ceiling over the garage, and a net exposed wall area of 169 m^2 (1824 ft^2) of which 18.6 m^2 (200 ft^2) are glass and 18.6 m^2 (200 ft^2) are interior wall adjoining the garage. Wall glass, and door areas, and U valves are shown in Table A-1. The total volume of the house, excluding the basement, garage, and unheated attic, is 362 cubic meters (12,800 ft^3). The thermal insulation meets



FIRST FLOOR PLAN

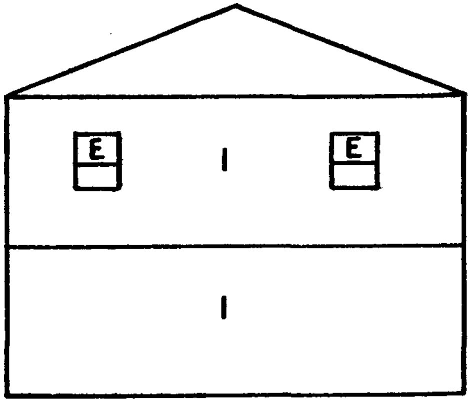
NORTH ELEVATION



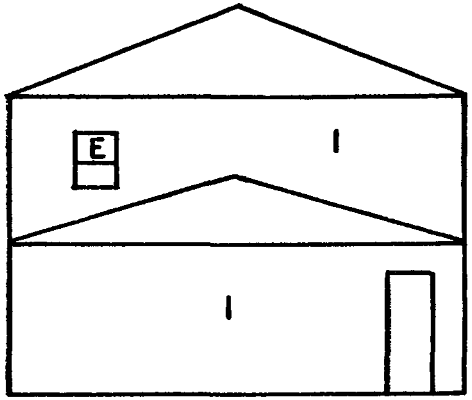
SECOND FLOOR PLAN

SOUTH ELEVATION

Figure A-1. Typical Home, Plans and Elevations (numbers and letters refer to construction data shown in Figure A-2)



EAST ELEVATION



WEST ELEVATION

CONSTRUCTION

1. Wall-Asbestos Siding Sheathing, 2.5 cm (1") Styrofoam Board, 7.5 cm (3") Fiberglas Batts, 1.2 cm (1/2") Plaster Board
   $U=0.35\ W/m^2{}^\circ C$
2. Wall - 10 cm (4") Face Brick, Sheathing, 2.5 cm (1") Styrofoam Board, 7.5 cm (3") Fiberglas, 1.2 cm (1/2") Plaster Board
   $U=0.36\ W/m^2{}^\circ C$
3. Wall - 1.2 cm (1/2") Plaster Board, 7.5 cm (3") Fiberglas, 1.2 cm (1/2") Plaster Board
   $U=0.43\ W/m^2{}^\circ C$

Roof - Dark Shingles

Upper Ceiling - 22.5 cm (9") Fiberglas, 1.2 cm (1/2") Plaster Board
$U=0.18\ W/m^2{}^\circ C$

Floor - Hardwood, 10 cm (4") Fiberglas
$U=0.074$

WINDOW AND DOOR TYPES

A. Wood w/storm

B. Fixed Glass, Thermopane

C. Double-Hung Wood w/Storm

D. Double-Hung Wood w/Storm

E. Double-Hung Wood w/Storm

F. Double-Hung Wood w/Storm

G. Fixed Glass, Thermopane

H. Sliding Glass, Thermopane

Figure A-2. Typical Home, Elevations and Construction Data the U.S. Department of Housing and Urban Development's "Minimum Property Standards". (Ref. A-1).

The indoor design conditions are 20°C (68°F) dry bulb in the winter, and 22.2°C (73°F) dry bulb in the summer.

A.2 HEATING LOAD

The space heating requirements for the typical home are shown in Table A-2. They were obtained using the TRNSYS computer program (Ref. A-2).

The calculated annual heating energy requirement was 64 GJ (60.9×10^6 Btu).

Table A-1. Typical Home Used for This Study

Wall	Wall Area m^2 (ft^2)	Glass Area m^2 (ft^2)	Door Area m^2 (ft^2)
North	34.8 (374.5)	9.3 (100)	3.5 (37.5)
South	39.9 (430)	7.6 (82)	
East	35.7 (384	1.5 (16)	
West (exposed)	17.8 (192)	0.7 (8)	
West (Adjoining Garage)	18.6 (200)		

U-Values	W/m^2 °C	(Btu/hr ft^2 °F)
Wall	.35	(.061)
Floor	.32	(.056)
Ceiling	.18	(.031)
Doors	3.5	(.62)
Window (double glass)	3.3	(.57)

Table A-2. Space Heating Requirements for Typical Single-Family Home in the Philadelphia Electric Company Service Area

Item	kJ/hr°C	(Btu/hr°F)
Roof	47.1	(24.8)
Wall	187.6	(98.8)
Windows	226.0	(119.0)
Door	44.3	(23.3)
Floor	85.5	(45.0)
Infiltration (@ 0.85 air exchange per hour)	442.5	(233.0)
TOTAL	1035.0	(543.9)

A.3 COOLING LOAD CALCULATION

Cooling load and conventional cooling system energy usage calculations were performed for the "typical" house using TRNSYS. These calculations were also performed by the Philadelphia Electric Company using procedures developed based on their experience in monitoring residential cooling energy usage. While, during any given hour, the conventional cooling system energy requirements as predicted by TRNSYS and the Philadelphia Electric Company's program might be significantly different, the total energy use during the cooling season should be essentially the same. To achieve this match, it was necessary to adjust the parameters in the TRNSYS model somewhat.

Hourly cooling loads were calculated for the reference house using 1968 Philadelphia weather data. The procedure used was essentially the same as the heating load calculations, except that in calculating cooling loads, a daily internal heat generation profile was added to the TRNSYS house model, the thermostat setting was changed and a factor for latent cooling load was included. The internal heat generation profile included the contribution from people and appliances and is shown in Table A-3.

Table A-3. Internal Heat Gain for All-Electric Home
May - September

Hour	Base Electric Load, kJ/hr (kW)	Internal Load From People, kJ/hr	(# People)	Total Internal Load, kJ/hr
0-10	2172 (.603)	1688	(4)	3860
10-12	3278 (.911)	422	(1)	3700
12-4	3678 (1.022)	422	(1)	4100
4-5	3864 (1.073)	1266	(3)	5130
5-6	4472 (1.242)	1688	(4)	6160
6-8	5612 (1.559)	1688	(4)	7300
8-9	5152 (1.431)	1688	(4)	6840
9-11	4862 (1.351)	1688	(4)	6550
11-12	3592 (0.998)	1688	(4)	5280

A thermostat setting of 22.2°C (72°F) was used to determine the sensible cooling load. Although this thermostat setting is somewhat low with respect to conserving energy, the high humidity during the Philadelphia cooling season necessitates the use of a low setting with residential cooling equipment to control the humidity in the conditioned space. The total cooling load (sensible and latent load) was estimated by multiplying the hourly sensible load by a factor of 1.3.

APPENDIX B
SYSTEM DESCRIPTIONS

B.1 INTRODUCTION

The space heating, water heating, and space cooling systems selected for evaluation are described in this Section. Included for comparison are both conventional, and solar systems. Off-peak storage is incorporated with both conventional and solar systems.

Electric resistance heating was chosen as the base system for performance comparison with the various heating systems. A conventional electric water heater was chosen as the base system for performance comparison. For the cooling systems, a conventional vapor compression air conditioner was chosen as the base for performance comparison. A larger number of systems were investigated. However, based on thermodynamic and other considerations, the number of systems was reduced. Several of the systems that were rejected are described along with those selected for evaluation.

B.2 SPACE HEATING SYSTEMS

A forced warm air duct system is used to deliver thermal energy to the conditioned space. The air stream in the duct is heated by either hot water or electrical resistance coils located within the duct. An electrically powered fan forces the warm air through the duct system so that thermal energy is provided to the entire conditioned living space. The electrical energy consumption of the delivery fan is not included in the calculated valves of electrical energy consumption of the various energy supply systems reported here. It is essentially the same for all systems, and therefore does not affect the results of this analysis.

A conventional electrical resistance heating system was chosen as the base heating system for this study. Resistance heating is assumed to be 100% efficient; therefore, the energy consumption of the house is equal to its heat loss. Since the electric energy is required whenever the house loses heat, electrical demand is closely coincident with low ambient temperatures. This causes the winter heating peak of electric utilities. That peak will become more accentuated as electric heating becomes more prevalent.

B.2.1 Resistance Heating With Off-Peak Storage

If a thermal energy storage (TES) device is added as shown in Figure B-1, electric energy use can be shifted to the off-peak period. The system shown uses an insulated water tank with an electric resistance heating element to provide off-peak energy storage. During the off-peak period the tank is heated to set temperatures based on the 11 pm or 12 pm temperature as described in Section 3.

During the peak period, the hot water from the tank is circulated through a heat exchange coil in the air duct where it heats the air being delivered to the load. The only energy consumption during the peak period is the small power demand of a pump or a fan used for heat transfer. Solid thermal storage devices have recently become commercially available in the U.S. They have been successfully used in Europe for many years.

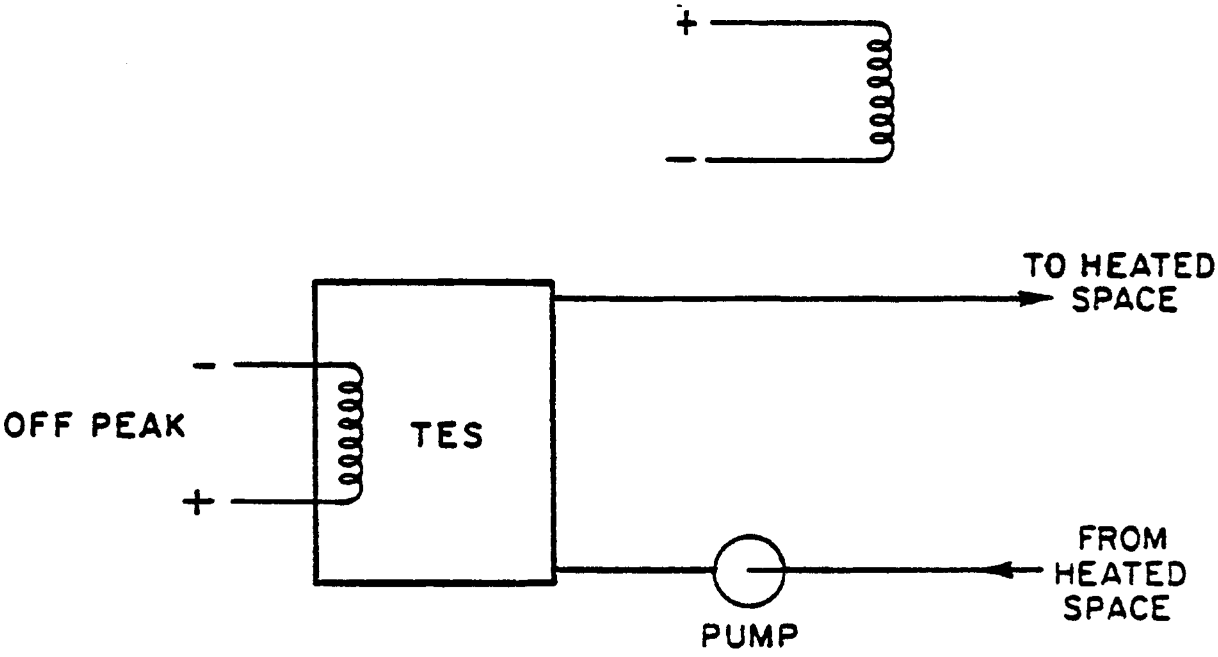


Figure B-1. Resistance Space Heating With Off-Peak Storage

B.2.2 Conventional Solar System

The major components of this system are shown schematically in Figure B-2. Water from an insulated storage tank is circulated through the collectors by a pump controlled by a differential thermostat. The pump circulates the water at a mass flow rate which corresponds to a flow rate through the collectors of 50 kg/m^2hr (1.22 $gal/hr\ ft^2$).

The differential thermostat turns the pump on whenever the temperature of the collectors is 5°C (9°F) above the temperature of storage. The pump will turn off when the temperature of the collectors is less than 1°C (1.8°F) above the storage temperature.

Thermal energy storage (TES) is provided by an insulated water storage tank. Hot water from the storage tank is circulated through a coil located in the air duct of the house to meet the heating load.

An electrical resistance coil, located downstream of the hot water coils in the duct provides auxiliary energy to the house whenever the solar system cannot meet the heating load.

As compared to solar heating systems which store energy off-peak, this system will use less auxiliary electrical energy because there are no storage losses from an off-peak TES to contend with. That is, auxiliary energy is used only when it is actually needed. However, since this auxiliary energy is most likely to be required during periods of cold weather, this system can contribute to utility winter peaks (Ref. B-1).

B.2.3 Solar Heating System With Off-Peak Energy in the Solar Storage Tank

A resistance heating coil is placed in the water storage tank of the conventional solar system. During the off-peak period, the storage tank temperature is raised to a level required to meet the anticipated peak period heating load. The anticipated load is determined using the 12 midnight temperature as discussed in Section 3. A schematic representation of this system is shown in Figure B-3.

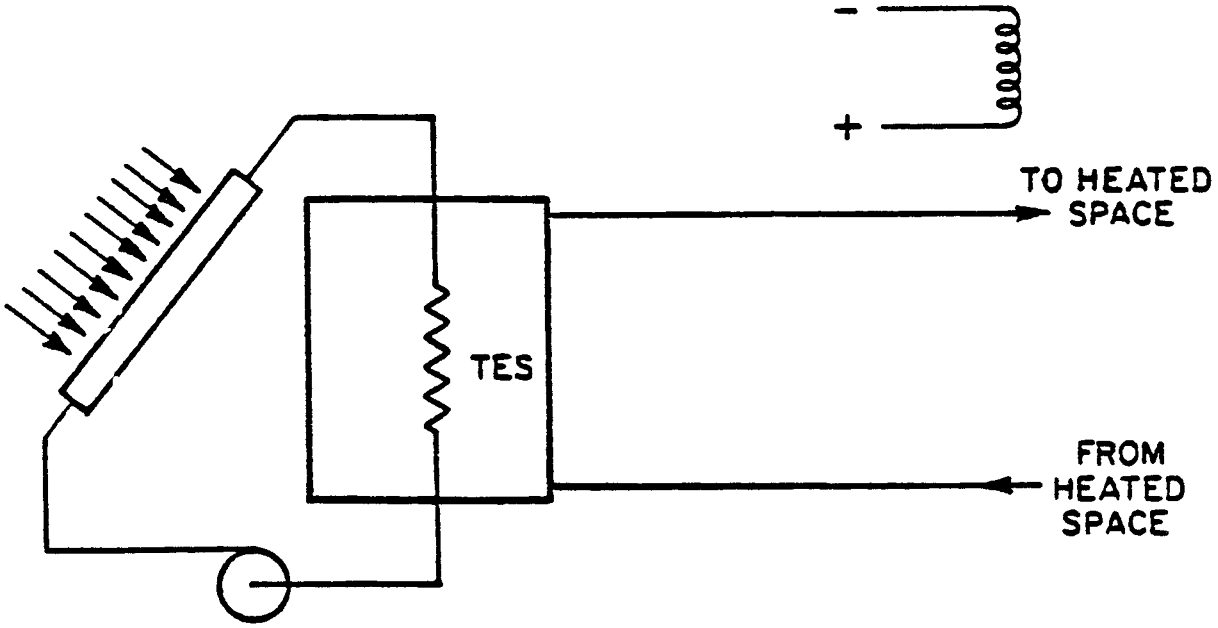


Figure B-2. Conventional Solar Space Heating System

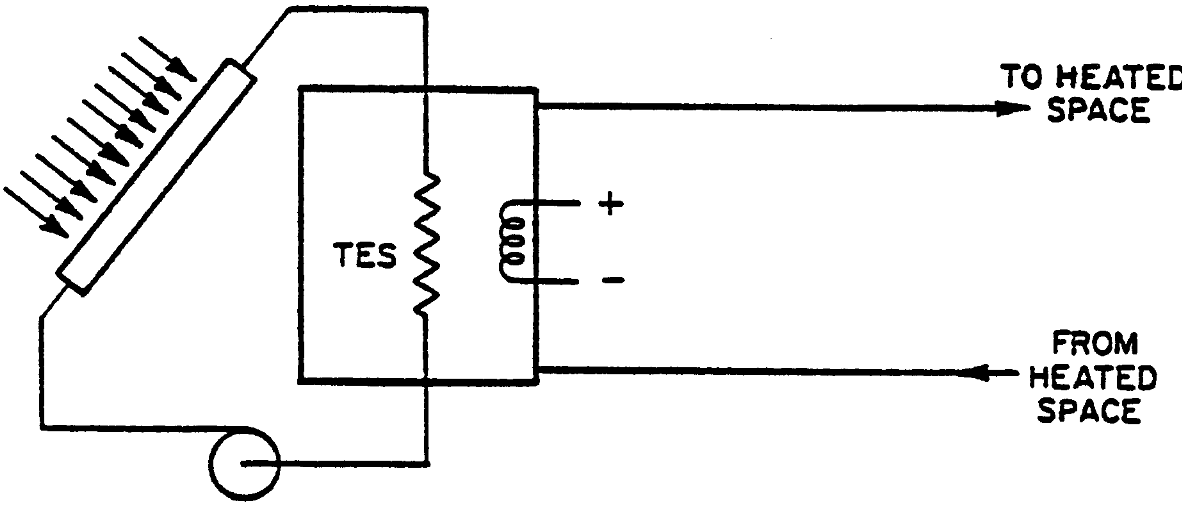


Figure B-3. Solar Heating System With Off-Peak Energy in the Solar Storage Tank

This solar system is identical to the conventional solar system, with the addition of a resistance heating coil in the storage tank, and with the removal of the duct mounted electrical heating coil.

While this eliminates on-peak demand, it results in greatly increased electrical energy consumption because:

1. the standby loss from storage is increased because of the higher storage temperature
2. collector efficiency on the following day is decreased because of the higher storage temperature.

B.2.4 Solar Heating System With a Separate Off-Peak Storage Tank

The system shown in Figure B-4 avoids the problems associated with the system shown in Figure B-3. In this system a second water storage tank is added to the conventional solar system for storage of off-peak energy. The second tank, hereafter referred to as the off-peak tank, is identical to the tank used in the resistance heating with off-peak storage system discussed in Subsection B.2.1. Charging of the off-peak tank is based on the 12 midnight temperature as discussed in Section 3. Components of the solar system (collectors, pumps, controller, and storage tank) are identical to those used in the conventional solar system described in Subsection B.2.2.

When there is a heating requirement, a choice between using hot water from the solar storage tank or from the off-peak storage tank to meet the load has to be made. Whenever the solar storage tank temperature is above 35°C (95°F) water from this tank is circulated through the hot water coil. However, if the solar storage temperature is below 35°C or the solar storage cannot meet the entire heating load, water from the off-peak storage tank is circulated through the coil to meet the load. By giving first use priority to the solar storage tank, its temperature is kept at a minimum. This allows the collectors to operate at optimal efficiency and to contribute as much energy as possible to the total heating load.

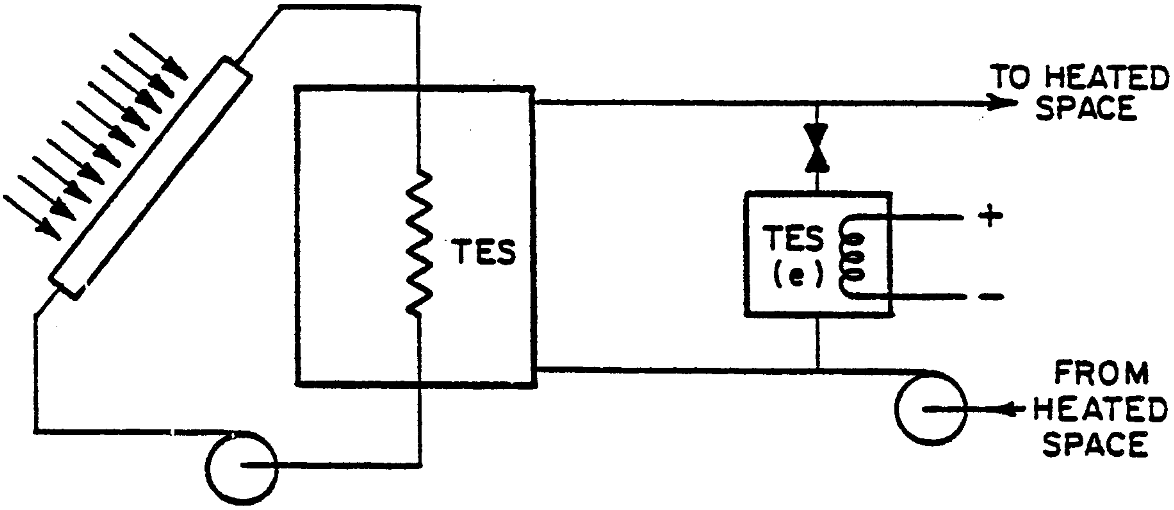


Figure B-4. Solar Heating System With a Separate Off-Peak Storage Tank

B.2.5 Solar System With a Separate Tank for Solar and Electrical Backup Storage

During periods of excess solar availability when the solar storage tank is fully charged, the addition of a second pump and several valves, as seen in Figure B-5, enables the second storage tank to be used for storage of solar as well as off-peak energy. However, it was felt that the benefit of the increased solar storage would not equal the cost of the additional pump and valving. Therefore, this system was not retained for further evaluation.

B.3 HEAT PUMP SPACE HEATING SYSTEMS

A conventional air-to-air heat pump system is shown in Figure B-6. It reduces total electrical energy consumption as compared to electric resistance heating, because the coefficient of performance (COP) of the heat pump is greater than one (1.0). The COP of electric resistance heating is at most one (1.0). But this system still contributes to the utility peak demand. As a matter of fact, during extremely cold periods, there is only a small difference in the electrical demand of resistance heating systems and heat pump systems.

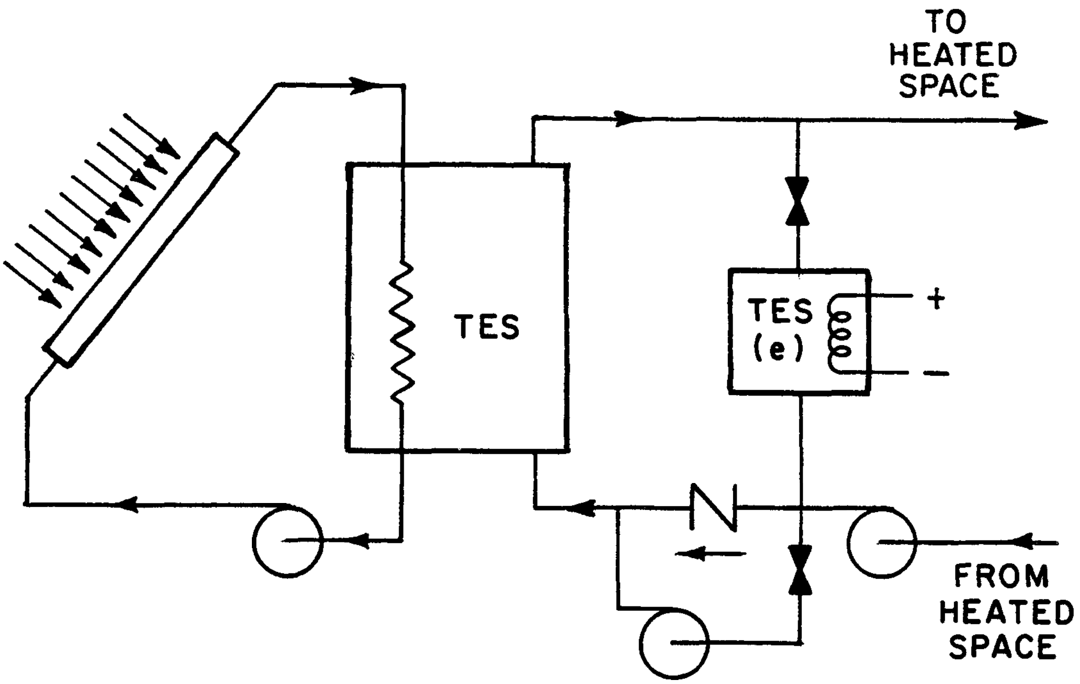


Figure B-5. Solar System with a Separate Tank for Solar and Electrical Backup Storage

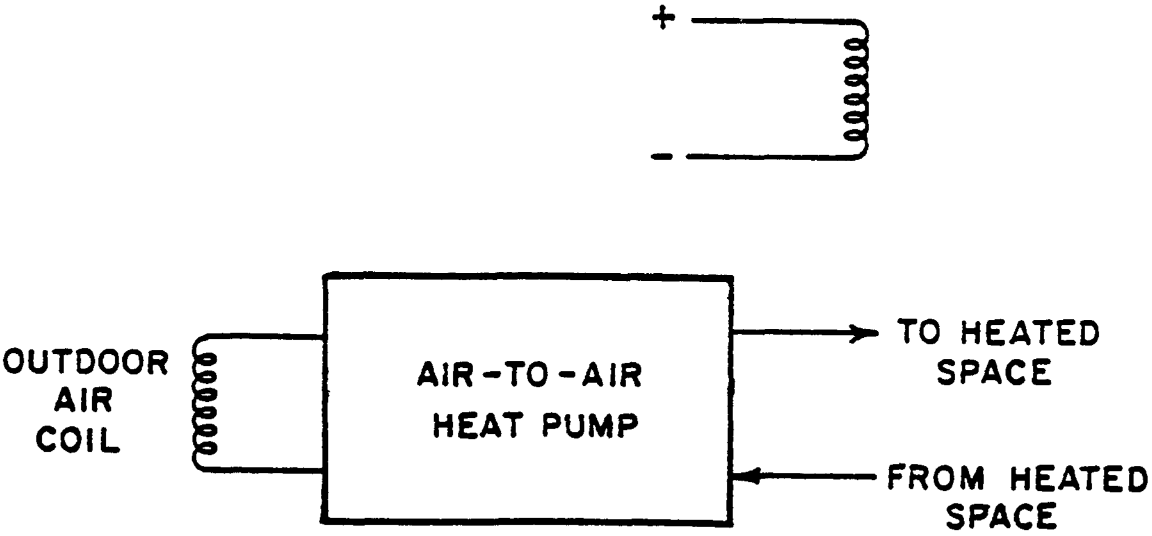


Figure B-6. Conventional Air to Air Heat Pump System

An outdoor evaporator coil extracts energy from the ambient air and an indoor condensing coil, located in the hot air duct, supplying energy to the heated space. For backup energy, a resistance heating coil is placed in the hot air duct downstream of the condenser coil to make up any portion of the heating load not met by the heat pump.

Performance data for a commercially available air-to-air heat pump (Ref. B-1) are shown in Figure B-7.

B.3.1 Heat Pump With Off-Peak Storage

The system shown in Figure B-8 contains a heat pump with off-peak hot water storage that can be used to reduce peak power demands. This is a so-called "dual source" heat pump because it has two evaporators; one extracts heat from ambient air, the other from hot water in storage. At least one U.S. manufacturer sells such a heat pump, and others are developing such types.

The water source evaporator is located in an insulated water storage tank. During every off-peak period of the heating season, the water tank is heated to 35°C (95°F), the maximum operating temperature for the water source evaporator.

Performance data for an air source heat pump (Ref. B-1) and a water source heat pump (Ref. B-2) are used to model the performance of the dual source heat pump. The air source evaporator has an operating range of -20°C to 20°C (-3°F to 67°F), and the water source evaporator has an operating range of 13°C to 34°C (55°F to 93°F). A performance graph indicating heating capacity and coefficient of performance (COP) versus evaporation temperature is shown in Figure B-9.

To minimize electrical energy input to the water storage tank, the air source evaporator is operated preferentially to the water source evaporator. Only when the air source evaporator cannot meet the full heating load is the water source evaporator used to make up the difference.

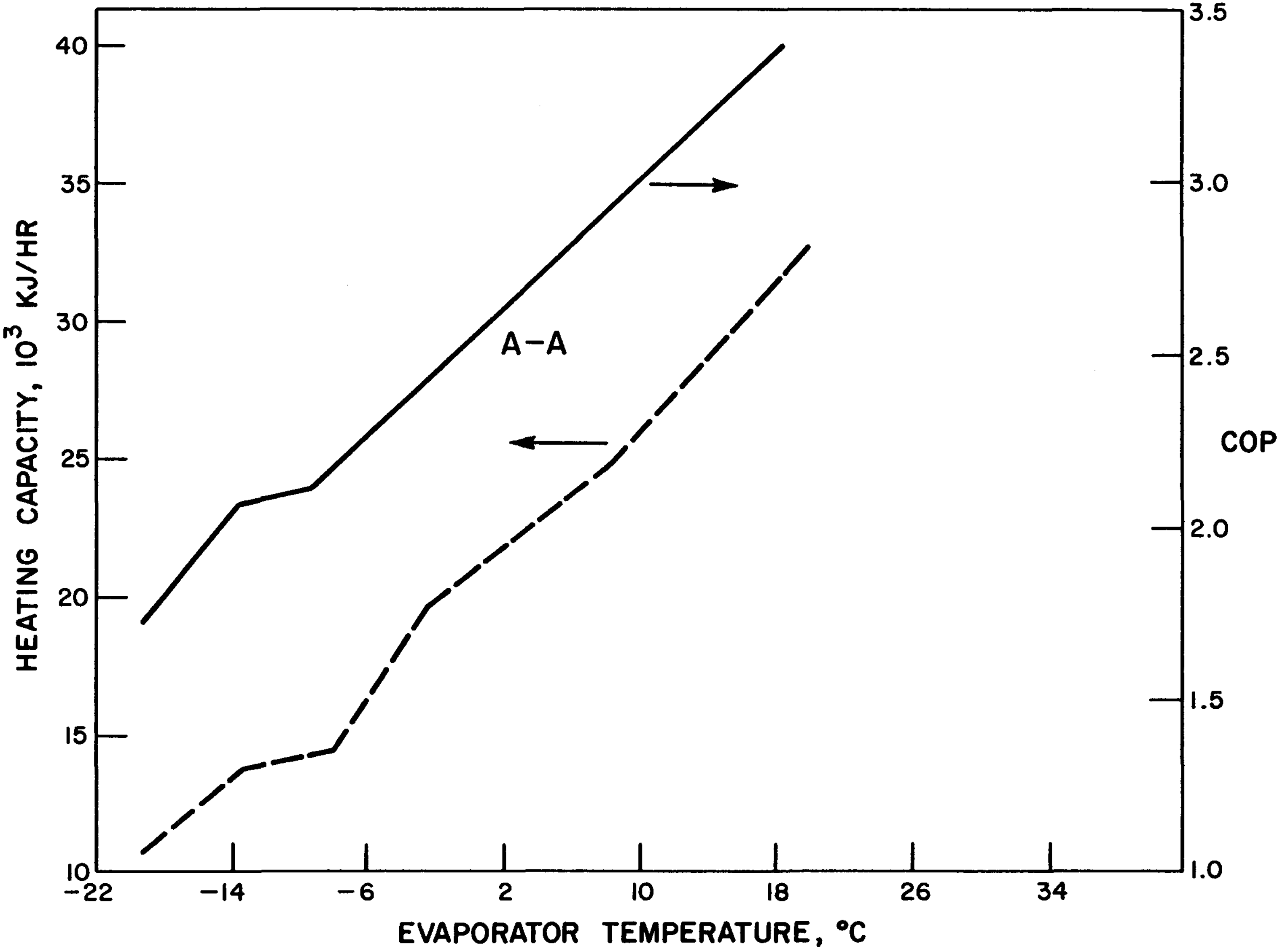


Figure B-7. Conventional Air to Air Heat Pump Performance

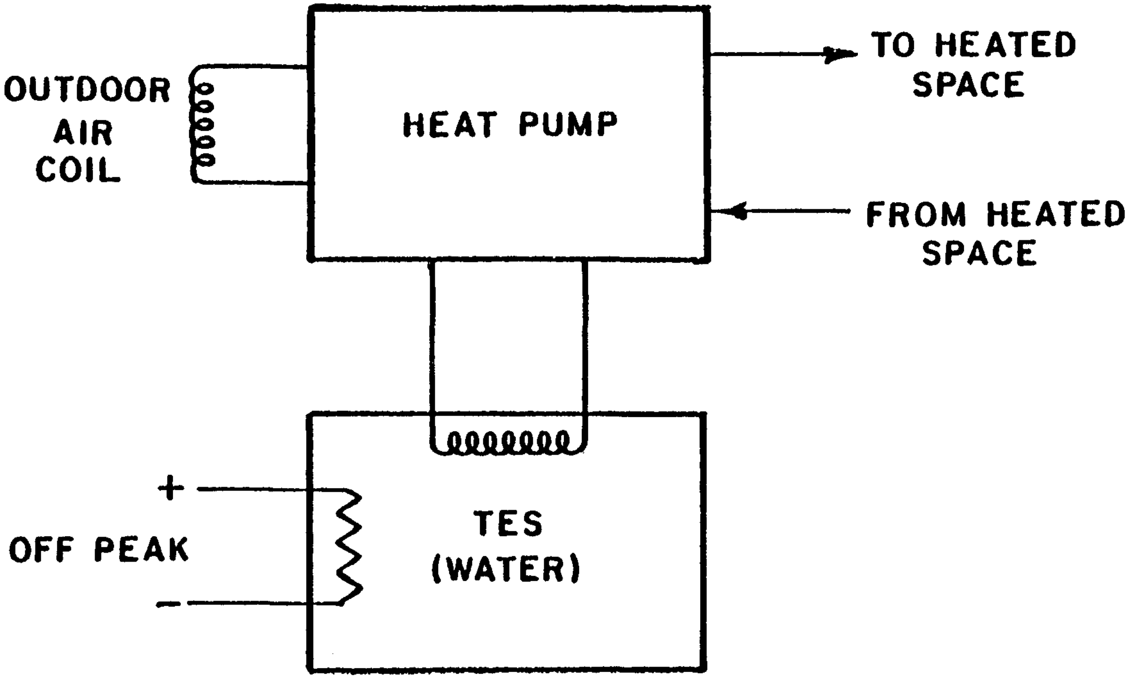


Figure B-8. Heat Pump with Off-Peak Storage

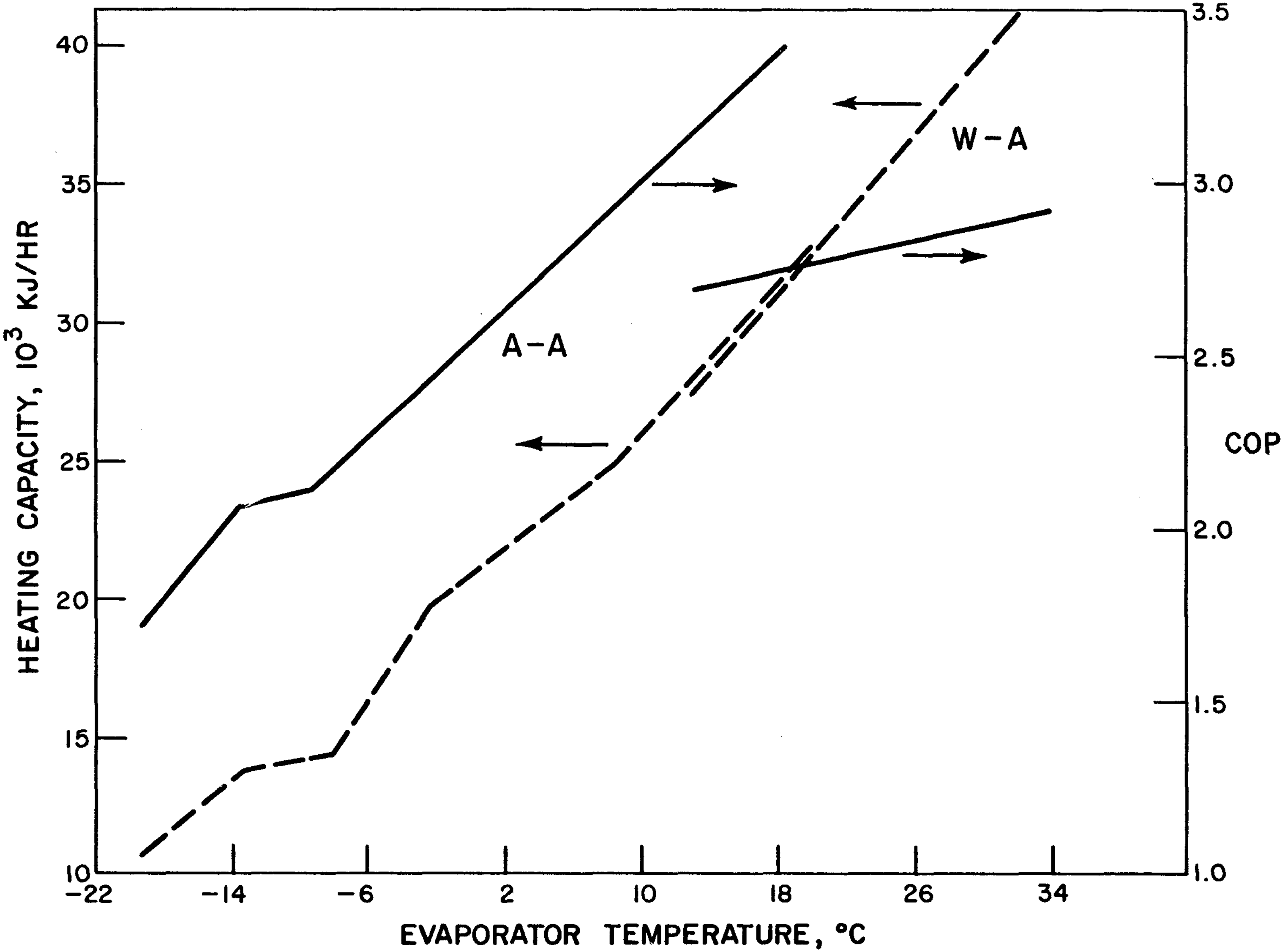


Figure B-9. Dual Source Heat Pump Performance

B.3.2 Solar Assisted Heat Pump

A solar assisted water-to-air heat pump is shown in Figure B-10. Because of its ability to utilize solar heated water at a relatively low temperature, a low storage temperature can be maintained. This increases the solar collector efficiency. However, this system can also cause high peak electrical demands.

A solar energy system is used to provide energy to a water-to-air heat pump (in series between the solar system and the load), which provides the required energy to meet the heating load to the hot air duct. Water from the storage tank of the solar system is circulated through the evaporator of the heat pump. A resistance heating coil, located downstream of the heat pump condensing coil, provides backup energy should the heat pump be unable to meet the entire heating load.

Performance data (Ref. B-2) for the water-to-air heat pump are shown in Figure B-11. The operating range of the water source evaporator is 13°C to 35°C (53°F to 95°F).

B.3.3 Solar Assisted Heat Pump With Off-Peak Storage in the Solar Storage Tank

To reduce the peak load power demand, an electric resistance heater is added to the water storage tank of the solar assisted heat pump. During off-peak hours, resistance heating coil is used to raise the storage tank temperature to 35°C (95°F) (the maximum operating temperature of the heat pump evaporator). A schematic representation of this system is shown in Figure B-12. Because of the low set temperature for the off-peak electric heating element, the use of a single tank for solar and off-peak storage does not affect collector efficiency significantly. The impact on storage losses is also minimal.

B.3.4 Solar Assisted Dual Source Heat Pump With Direct Heating from Solar

In this system (refer to Figure B-13), a dual source heat pump is used in conjunction with a solar collection system to provide energy for

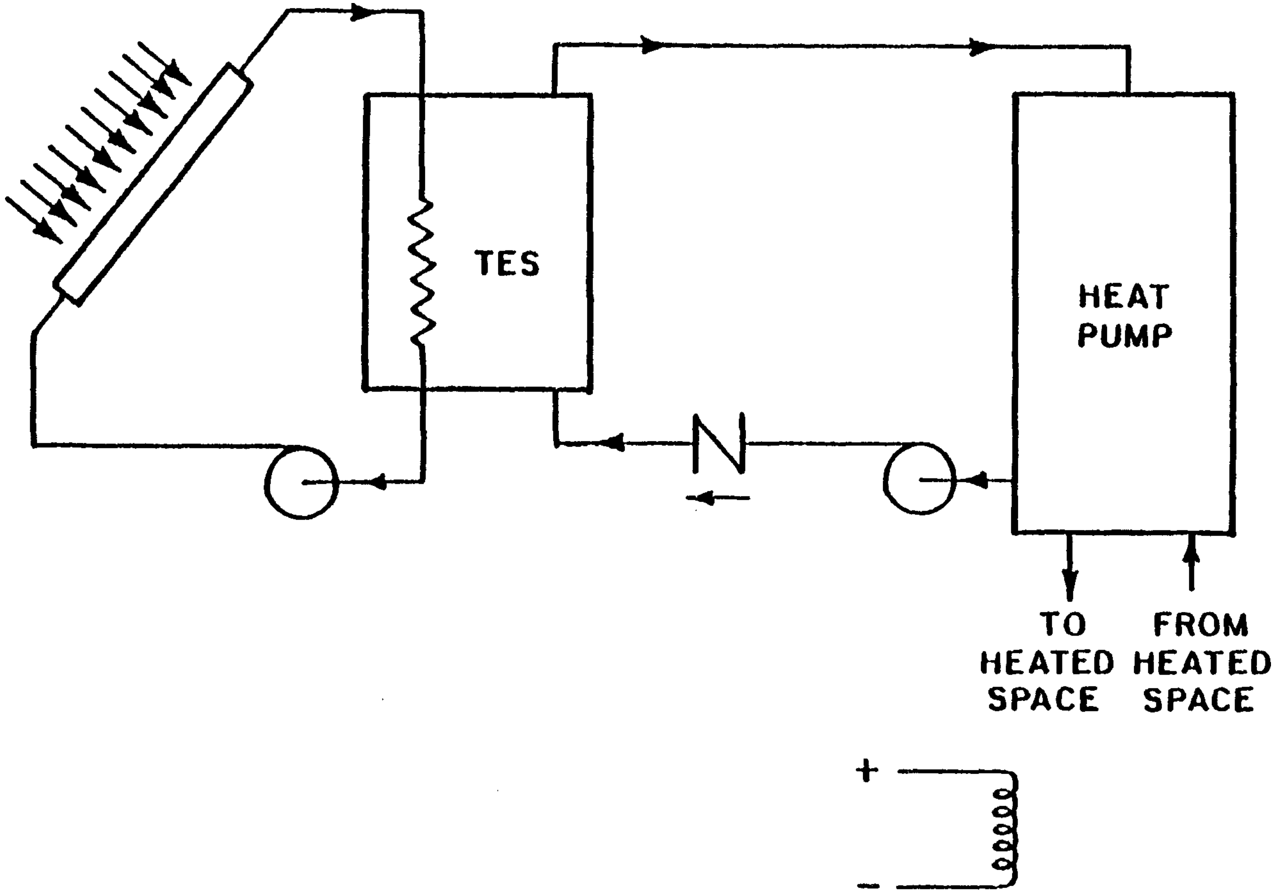


Figure B-10. Solar Assisted Heat Pump

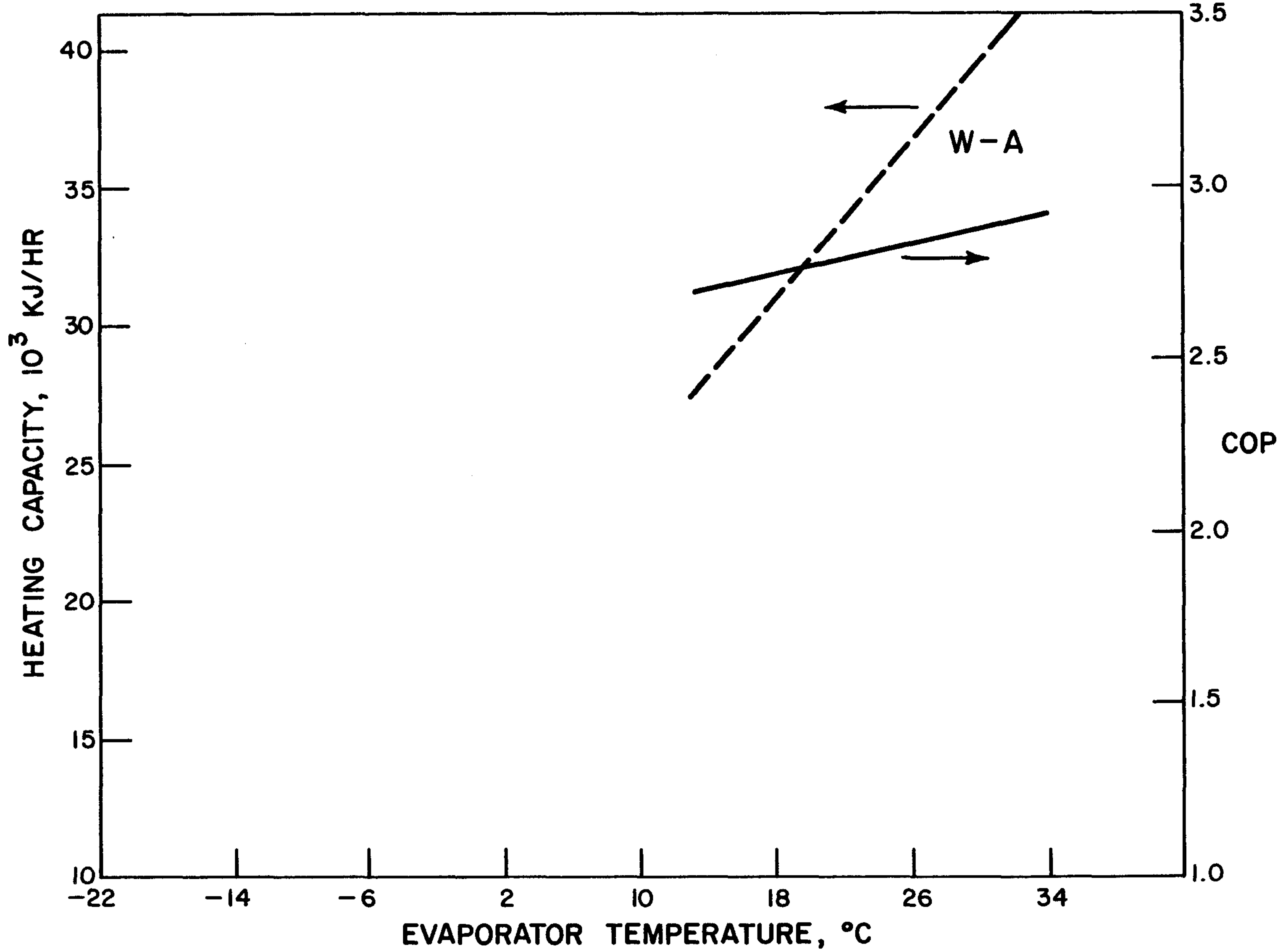


Figure B-11. Water to Air Heat Pump Performance

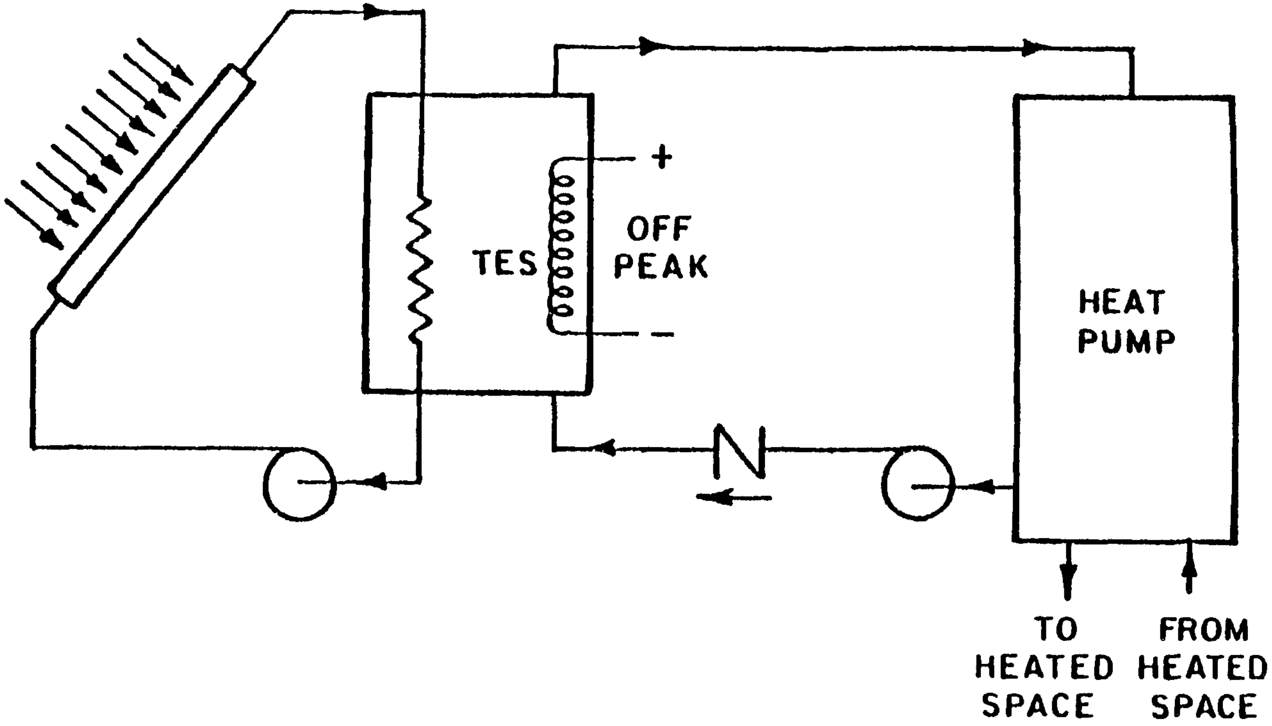


Figure B-12. Solar Assisted Heat Pump With Off-Peak Storage in the Solar Storage Tank

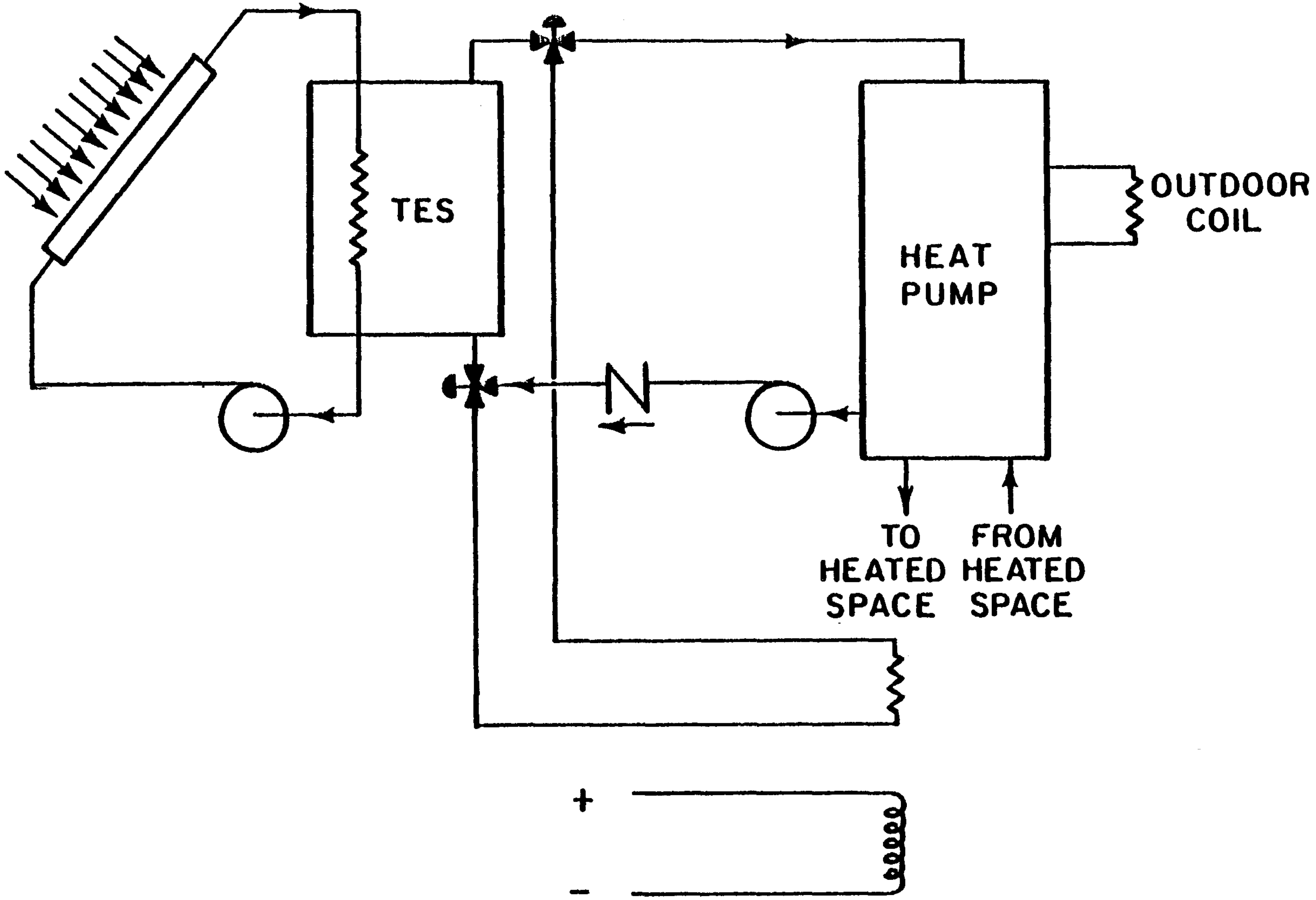


Figure B-13. Solar Assisted Dual Source Heat Pump with Direct Heating from Solar space heating. The water source evaporator is connected to the solar storage tank from which it draws its energy during the water-to-water mode operation of the heat pump. The second evaporator is an outdoor air coil used in the heat pump's air-to-air mode. In addition, a water coil located in the hot air duct is connected to the solar storage tank to provide energy from the tank directly to the load. Backup energy is provided by a resistance heating coil in the hot air duct.

To maximize the utilization of solar energy the following control strategy is used. When the storage tank temperature is above 35°C (95°F), water from the tank is circulated through the water coil in the hot air duct providing solar energy directly to the load. When the storage tank temperature is between 13°C (55°F) and 35°C (95°F), the heat pump is operated in the water to air mode. Should the storage tank temperature drop below 13°C (55°F), the heat pump is operated in the air to air mode to meet the heating load. When the heating load cannot be met by either of these methods, the resistance heating coil is used to satisfy the demand. These control rules are listed in Table B-1.

Table B-1. Control Rules for Solar Assisted Dual Source Heat Pump with Direct Heating

Storage Temperature	Operating Mode
TES > 35°C	Direct Solar Heating
13°C < TES < 35°C	Water to Air Heat Pump
TES < 13°C	Air to Air Heat Pump With Resistance Back-up

B.3.5 Solar Assisted Dual Source Heat Pump With Direct Heating and Off-Peak Energy Storage in the Solar Storage Tank

This system is identical to the solar assisted dual source heat pump with direct heating with the addition of off-peak storage in the solar storage tank. A resistance heating coil is used to heat the storage tank to 35°C (95°C) during every off-peak period of the heating season. Figure B-14 shows the configuration of this system.

Details of the components used in this system are described in Section B.3.4. The control strategy used to operate this system is identical to that described in Section B.3.4 with the addition of charging of the off-peak storage to 35°C during the off-peak period. Table B-2 lists the control rules for this system.

Table B-2. Control Rules for Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Storage In-Tank

Storage Temperature	Operating Mode
TES > 35°C	Direct Solar Heating
13°C < TES < 35°C	Water to Air Heat Pump
TES < 13°C	Air to Air Heat Pump
TES < 35°C Off-Peak Hours	Charge TES

B.3.6 Solar Assisted Dual Source Heat Pump With Direct Heating and a Separate Off-Peak Storage Tank

In this system a separate off-peak storage tank is added to the solar assisted dual source heat pump system of Section B.3.4. The off-peak storage tank is heated to 35°C (95°F) during every off-peak period of the heating season. The remaining components of this system are identical to those of the solar assisted dual source heat pump with direct heating from solar described in Section B.3.4. A schematic representation of this system is shown in Figure B-15.

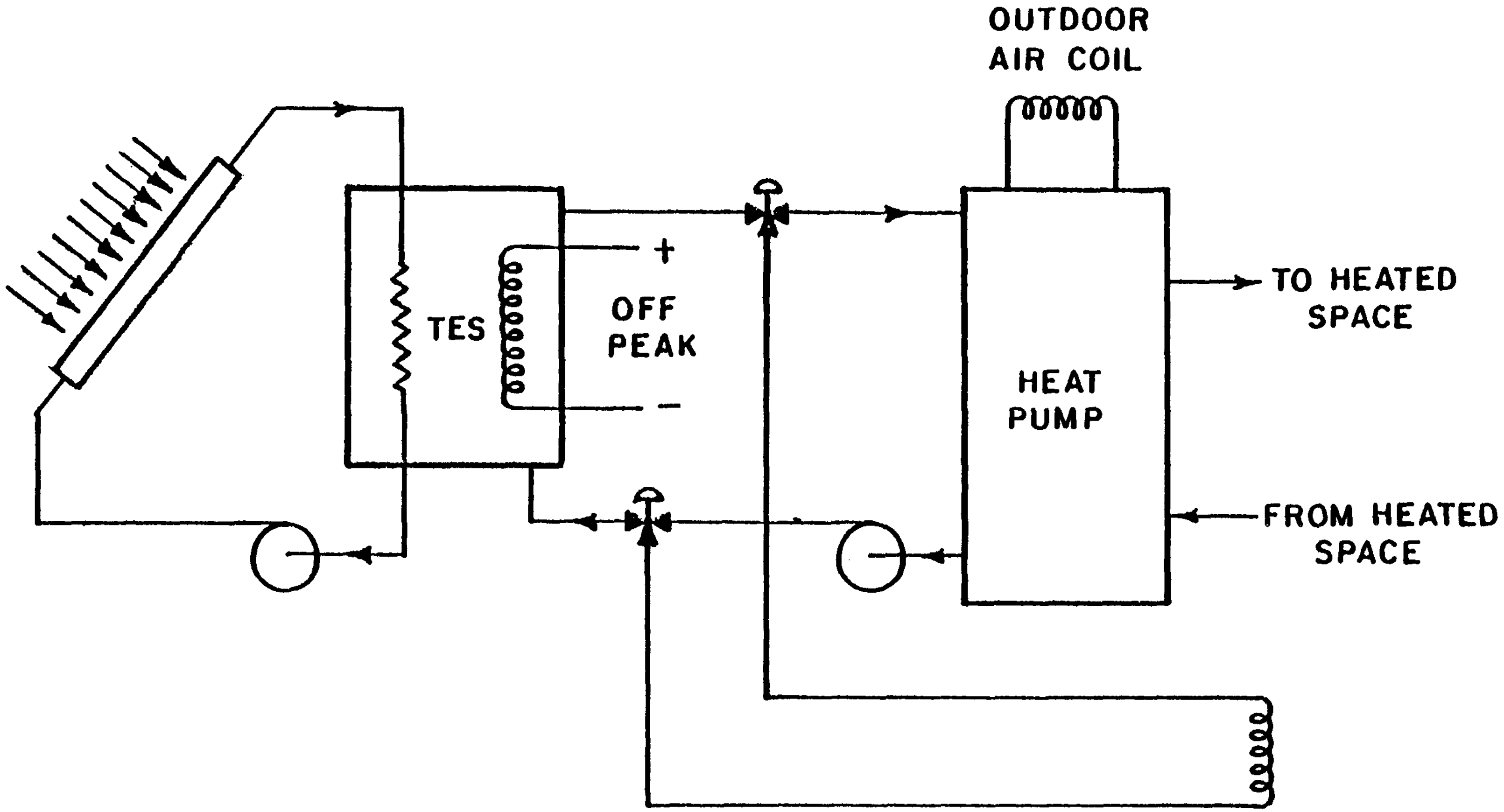


Figure B-14. Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Energy Storage in the Solar Storage Tank

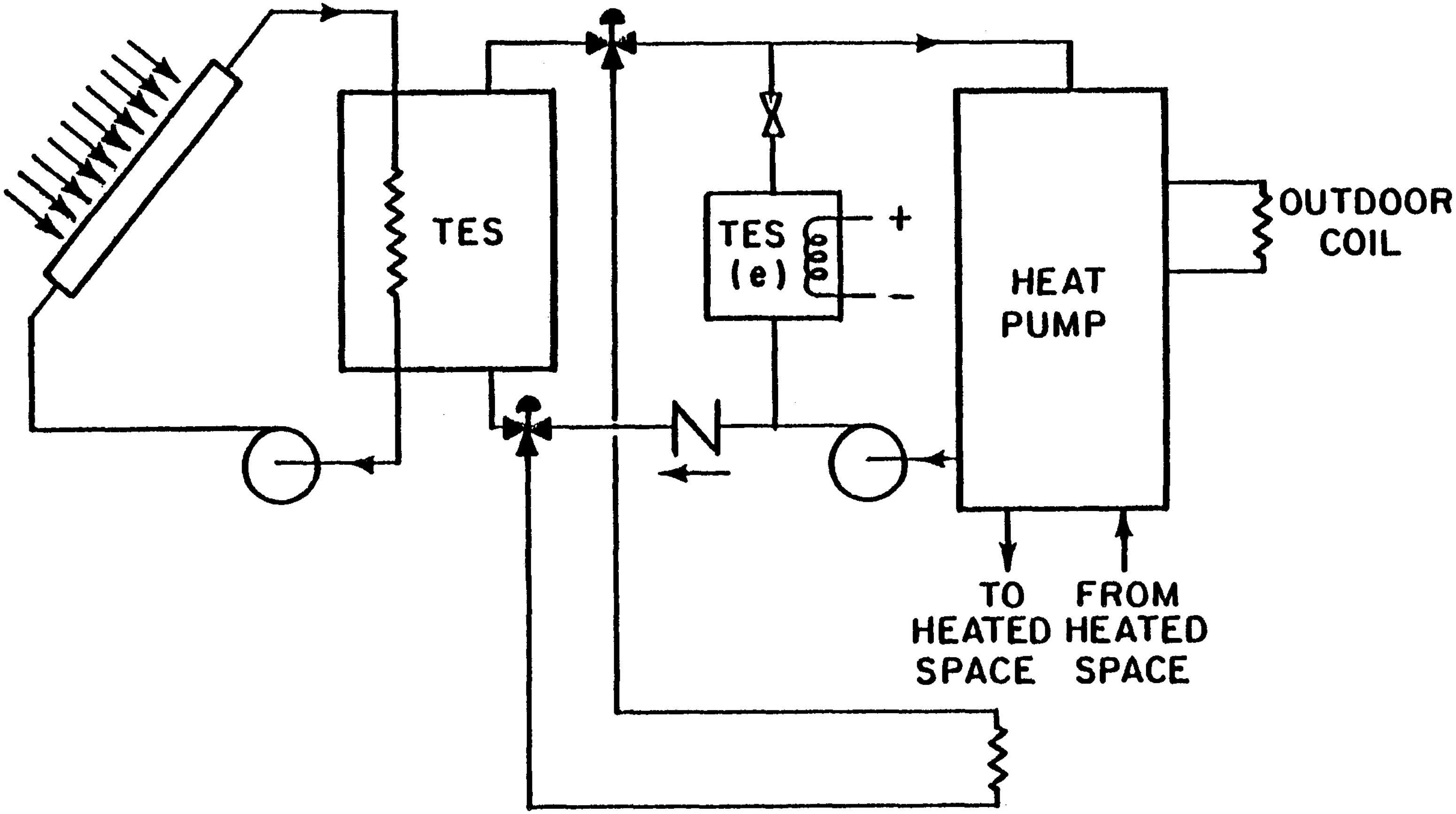


Figure B-15. Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Energy Storage in a Separate Tank

In order to achieve maximum utilization of the solar system, the following control strategy is employed. When the solar storage tank temperature is above 35°C (95°F), water from the tank is circulated through the water coil in the hot air duct providing solar energy directly to the load. When the solar storage tank temperature is between 35°C (95°F) and 19°C (66°F), water from the solar tank is used to operate the heat pump in the water to air mode. Although the minimum useful source temperature of the heat pump in this mode is 13°C (55°F), the heat pump cannot meet the design heating load at that temperature. Therefore, when the solar storage tank temperature drops below 19°C (66°F) and the off-peak tank temperature is between 35°C (95°F) and 13°C (55°F), water from the off-peak tank is used to operate the heat pump in the water to air mode. Should the off-peak tank temperature drop below 13°C (55°F), the heat pump is operated in the air to air mode. During each off-peak period, the off-peak storage tank is heated to 35°C (95°F). This tank is sufficiently large to satisfy the house heating demand in the water to air heat pump mode during the following on-peak period. Thus, no back-up electrical resistance coil is required in this system. The control rules are listed in Table B-3.

Table B-3. Control Rules for Solar Dual Source Heat Pump with Direct Heating and a Separate Off-Peak Storage Tank

Storage Temperature	Operating Mode
TES > 35°C	Direct Solar Heating
19°C < TES < 35°C	Water to Air Heat Pump
13°C < TES(e) < 35°C	Water to Air Heat Pump
TES(e) < 13°C	Air to Air Heat Pump
TES(e) < 35°C Off-Peak Hours	Charge TES

B.4 DOMESTIC WATER HEATING SYSTEMS

Domestic hot water is supplied to the house faucets through a standard plumbing system including a mixing (or tempering) valve, connected between hot and cold water lines, to provide scald protection. Heat losses from the hot water lines between the mixing valve and the faucets were not included in this study. These losses would be the same for all systems and therefore do not effect the results of this comparative study.

A standard insulated water heater with two electric heating elements was chosen as the base water heating system for this study. This system is shown schematically in Figure B-16. The temperature in the water heater is maintained at a constant set temperature of 60°C (140°F). Whenever the water temperature drops below this set temperature, the heating elements are energized until the set temperature is reached.

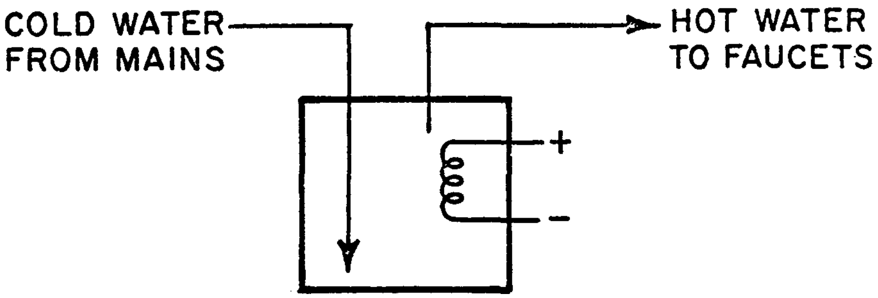


Figure B-16. Resistance Water Heater

B.4.1 Off-Peak Resistance Water Heating

For off-peak resistance water heating a slightly larger water heater is used in conjunction with an off-peak timer. During the off-peak period the heating elements heat the water up to 70°C (158°F) and maintain it at that temperature. During the on-peak period the off-peak timer disables the heating elements so that no energy is used. When hot water is required, water from the heater is mixed with cold water using the mixing (tempering) valve so that 60°C (140°F) water is supplied to the faucets. The larger water heater and higher water set temperature allow the entire hot water load to be met without the use of any auxiliary energy during the on-peak period.

B.4.2 Conventional Solar Water Heating

The major components of this system are shown schematically in Figure B-17. Water from an insulated storage tank is circulated through the collectors by a pump controlled by a differential thermostat. The pump circulates the water at a mass flow rate corresponding to a flow rate through the collectors of 50 kg/m^2hr (1.22 $gal/hr\ ft^2$).

The differential thermostat turns the pump on whenever the temperature of the collectors is 5°C (9°F) above the temperature of storage. The pump will turn off when the temperature of the collectors is less than 1°C (1.8°F) above the storage temperature.

Thermal energy storage (TES) is provided by an insulated water storage tank. Cold water from the city mains is drawn into the bottom of the storage tank as warm solar heated water is drawn from the top of the tank. This solar heated water is then fed to a conventional electric water heater where the water is heated, if necessary, to 60°C (140°F). By providing solar heated water to the conventional water heater rather than cold water directly from the city mains the auxiliary energy requirements of the water heater are substantially reduced.

B.4.3 Solar Water Heating With Off-Peak Storage

This system is identical to the Conventional Solar Water Heating System shown in Figure B-17 with a slightly larger water heater used and the addition of an off-peak timer which disables the heating elements in the water heater during the on-peak period. During the off-peak period the water heater temperature is raised to and maintained at 70°C (158°F). When hot water is required, solar heated water is drawn from the top of

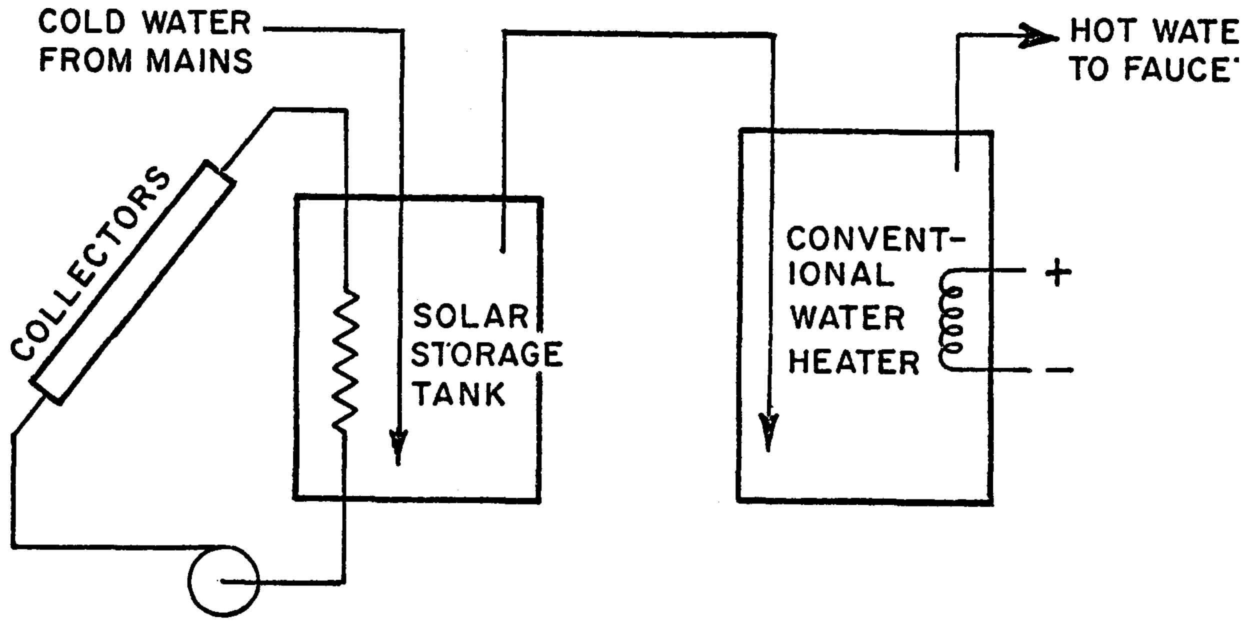


Figure B-17. Conventional Solar Water Heating System

the solar tank into the bottom of the water heater which in turn delivers water at the desired temperature of 60°C (140°F) to the faucets via the mixing tempering valve.

Since the heating elements in the water heater are disabled duirng the on-peak period the only energy consumption throughout this time period is from the pump used to circulate water through the solar collectors.

B.4.4 Conventional Solar Space and Water Heating System

Figure B-18 shows the major components of this combined space and water heating system. This system is identical to the Conventional Solar Space Heating System described in Section B.2.2 with addition of an electric water heater and a heat exchange coil in the solar thermal energy storage (TES) tank. When hot water is required, cold water from the city mains is drawn through the heat exchange coil, where it picks up heat from the solar storage tank. This solar pre-heated water is subsequently drawn into the conventional electric water heater where the water temperature is maintained at 60°C (140°F) to supply hot water to the faucets.

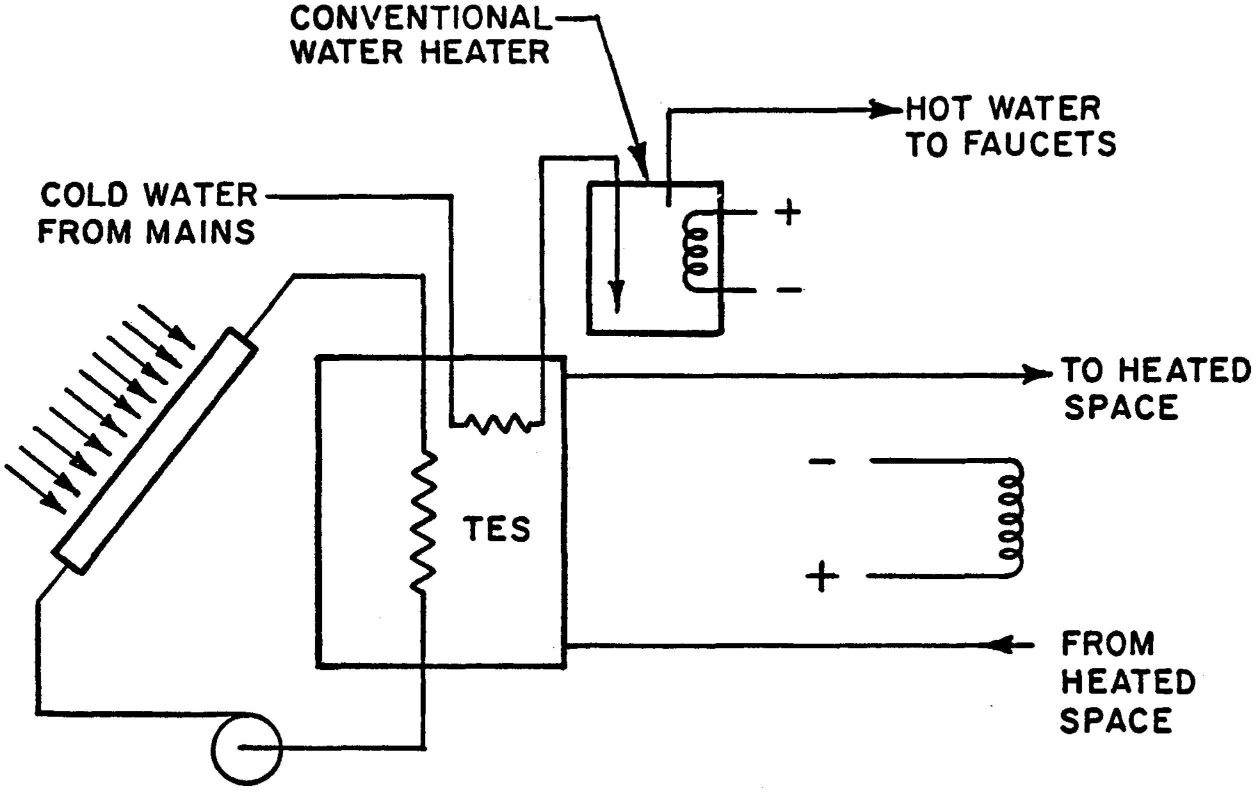


Figure B-18. Conventional Solar Space and Water Heating System

Operation of the solar space heating portion of this system is identical to that described in Section B.2.2.

B.4.5 Solar Space and Water Heating With Off-Peak Storage

The major components of this system are shown schematically in Figure B-19. This system is identical to that of the Conventional Solar Space and Water System with the addition of an off-peak storage tank for space heating, a larger electric water heater replacing the water heater in the conventional system, and an off-peak timer added to disable all of the heating elements during the on-peak period.

Operation of the water heating portion of this system is similar to that described in the preceding section except that the heating elements in the water heater are disabled at all times except the off-peak period when the water is heated to 70°C (158°F). The space heating portion is operated in the manner described in Section B.2.5.

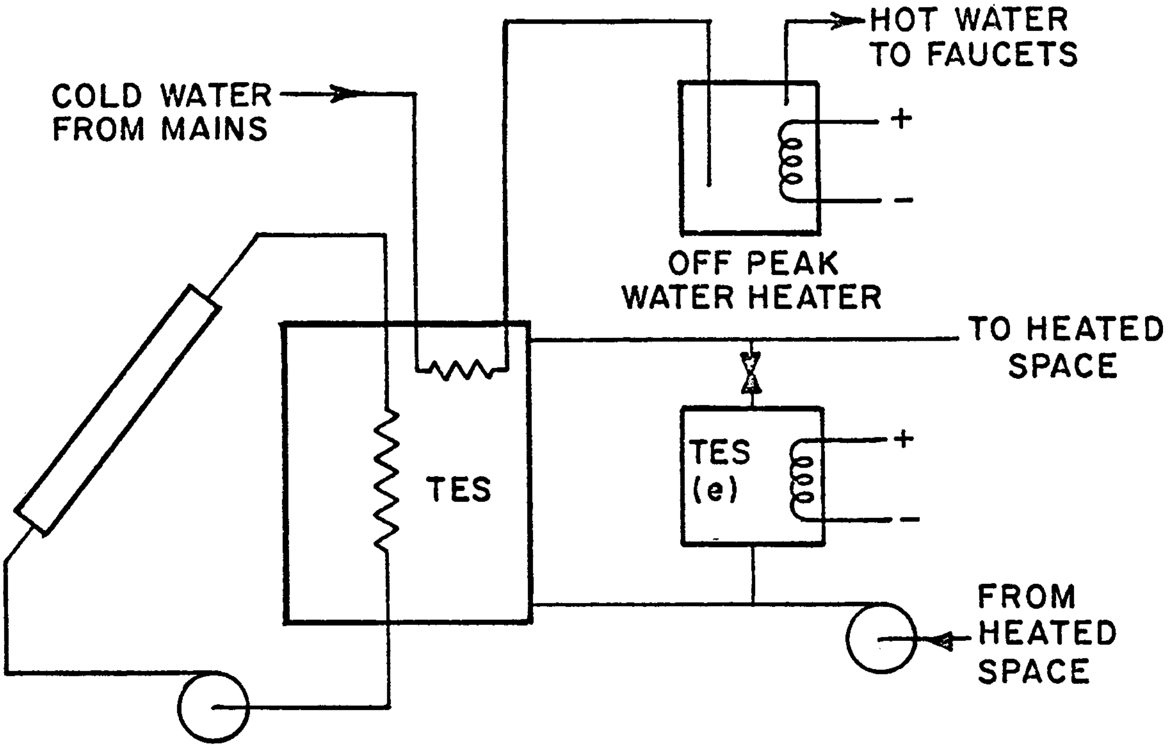


Figure B-19. Solar Space and Water Heating With Off-Peak Storage

Since all heating elements are disabled during the on-peak period, the only energy consumption during that time is from the solar collector pump and the pump which circulates hot water from the storage tanks to the space heating load.

B.5 SPACE COOLING SYSTEMS

The ever increasing use of space cooling systems contributes to the continual increase in the summer peak loads of many utilities. Solar powered cooling systems have the potential to provide utility customers with air conditioning and simultaneously reducing the contribution of air conditioning to utilities' summer peaks by utilizing solar energy instead of electricity. In this study, solar powered lithium bromide absorption chillers with auxiliary electric firing were evaluated as possible alternatives to the use of vapor compression air conditioners.

Four different solar powered absorption cooling systems were considered. These systems are shown schematically in Figures B-20 through B-23. Note that the cooling towers which are required by absorption chillers are not shown in Figures B-20 through B-23. In all cases, the storage medium is hot or chilled water. For each of the four systems, the operation of the solar collector subsystem is independent of the operation of the cooling system. A differential thermostat compares the temperature at the outlet of the solar collectors to the temperature at the bottom of the solar storage tank. The collector loop pump is started when the temperature at the collector outlet is 5°C (9°F) greater than the temperature at the bottom of the solar storage tank. The pump continues to run until the temperature at the collector outlet decreases to within 1°C 91.8°F) of the temperature at the bottom of the solar storage tank.

The system shown schematically in Figure B-20 represents a conventional solar absorption air conditioning (A/C) system. The absorption chiller is activated whenever there is a demand for cooling as indicated by a space thermostat. The preferred mode of operation is for hot water from solar storage to be pumped through the absorption chiller's generator heat exchanger and power the machine. This will occur if the temperature of solar storage is greater than or equal to 77°C (170.6°F), the machine's capacity is greater than 60% of its rated capacity as determined by the generator inlet and cooling tower return temperatures, and the capacity is sufficient to meet the load. If all three of these conditions do not

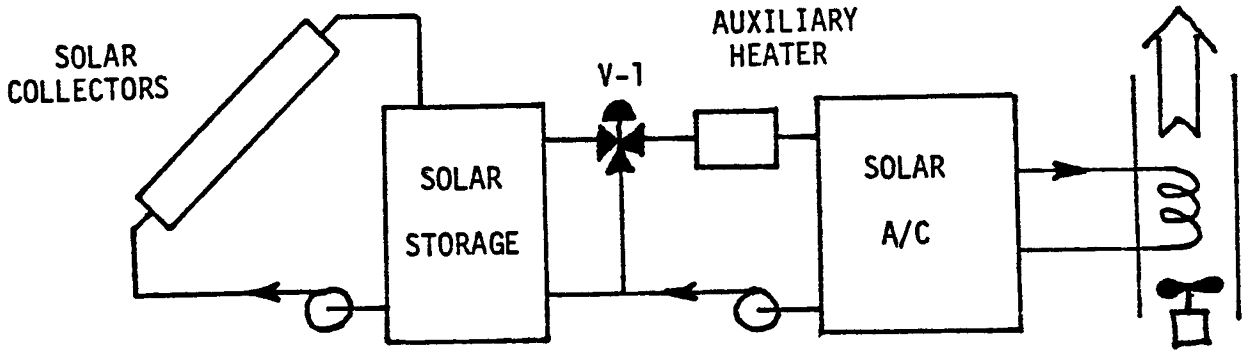


Figure B-20. Conventional Solar A/C

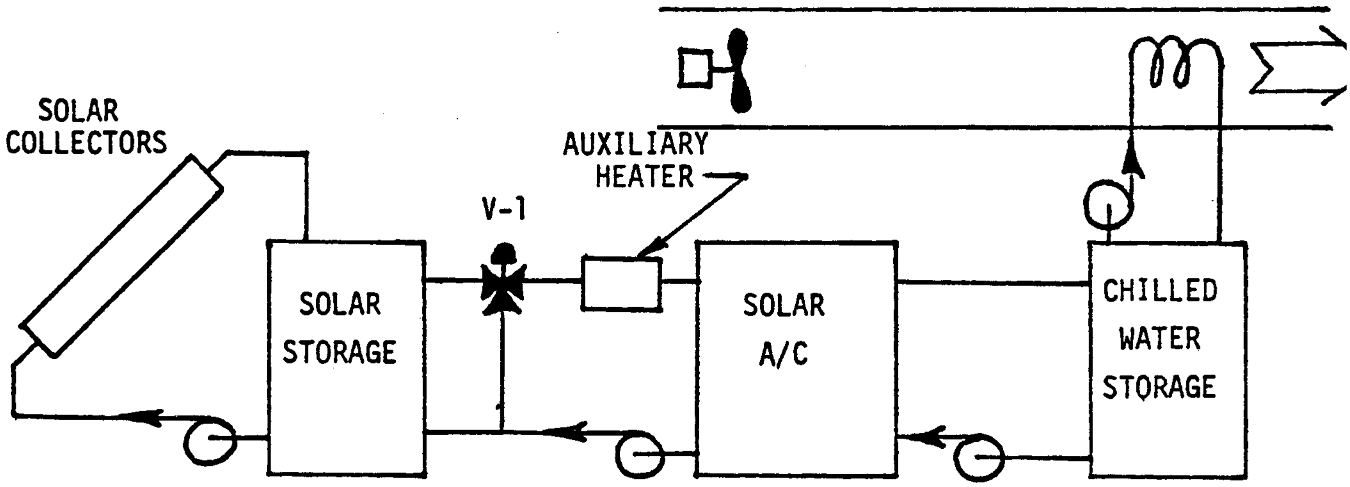


Figure B-21. Solar A/C with Chilled Water Storage

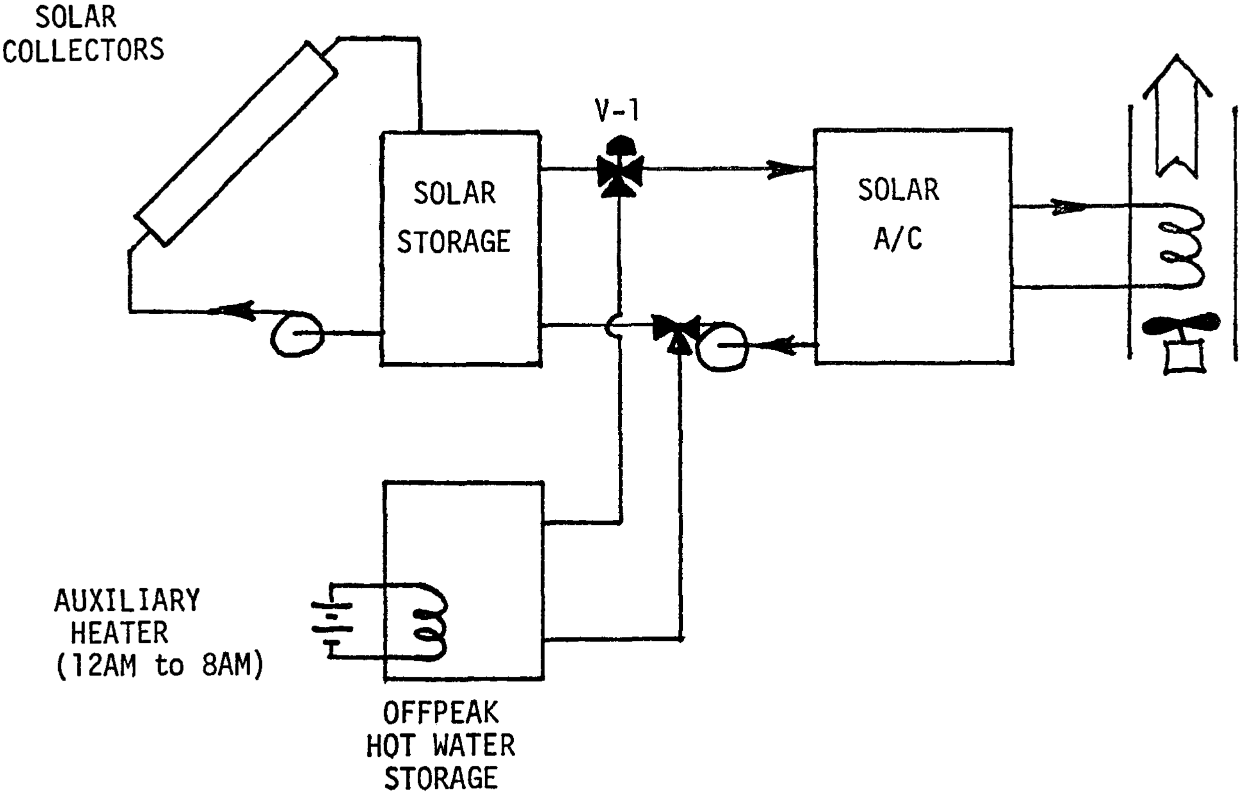


Figure B-22. Solar A/C with Off-Peak Hot Water Storage

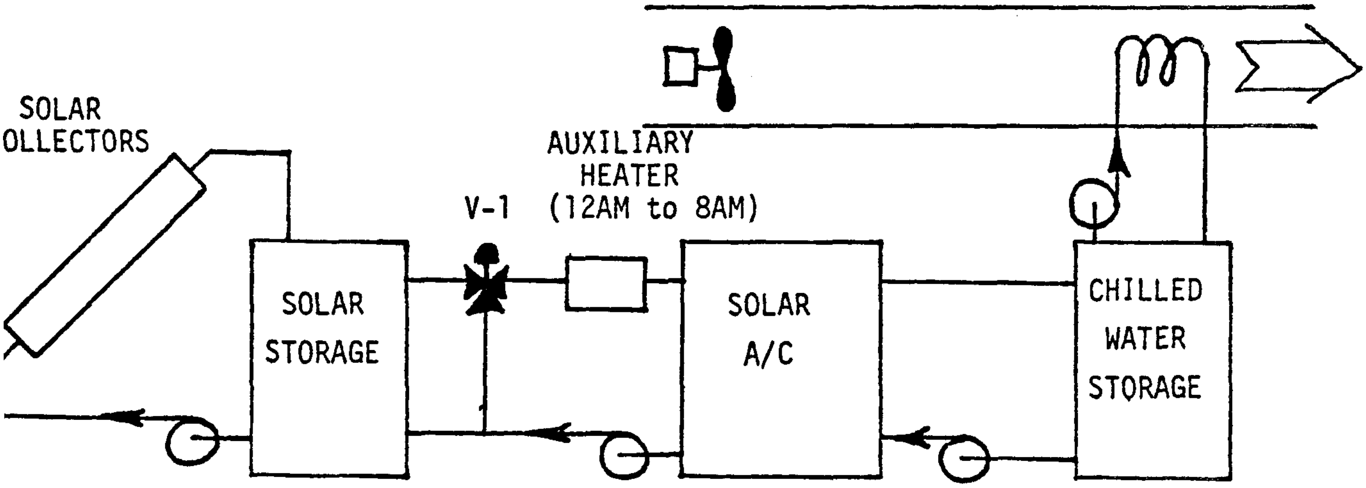


Figure B-23 . Solar A/C with Off-Peak Chilled Water Storage exist, valve V-1 bypasses solar storage and thermal energy is supplied to the generator by means of an auxiliary electric heater. Chilled water is pumped through the evaporator of the absorption chiller and circulated through a duct mounted heat exchanger. If the chiller's capacity at any given time is greater than the cooling load, the chiller's capacity is assumed to be modulated by an internal generator bypass circuit so that cycling of the machine is minimized. When the auxiliary electric heater is in operation, the chiller's full capacity is available, if necessary, to meet the load.

The system shown in Figure B-21 is similar to that in Figure B-20, however, there is now a chilled water storage tank to act as a buffer between the absorption chiller and the load. The rationale for supplying either solar or electrically heated hot water to the absorption chiller is the same as for the system shown in Figure B-20. In this case, however, the operation of the absorption chiller is controlled based on the temperature in the chilled water tank rather than by the space thermostat. The space thermostat activates the pump which circulates chilled water from the chilled water storage tank through the duct mounted heat exchanger. If the temperature in the chilled water tank is between 8°C and 15.6°C (46.4°F and 60°F) the chiller is only activated when the temperature of solar storage is greater than 77°C (170.6°F). If the temperature in the chilled water tank reaches 15.6°C (60°F), the absorption chiller is fired by the auxiliary electric heater if the temperature of solar storage is less than 77°C (170.6°F). The use of chilled water storage can minimize short term cycling of the chiller and thus reduce system losses associated with the startup transients that affect absorption units and can also result in a decrease in the chiller capacity required (Ref. 4-2).

The system shown in Figure B-22 is similar to the one in Figure B-20 with the exception that auxiliary energy for the solar A/C is supplied in the form of hot water heated electrically during an offpeak period (typically 12AM - 8AM). The usable temperature range for the offpeak hot water storage is 77°C to 104°C (170.6°F to 220°F). The solar air conditioner operates in response to a signal from the space thermostat. As with the system shown in Figure B-20, the preferred mode of operation is to use hot water from solar storage if possible. This will occur if the solar storage temperature is greater than or equal to 77°C (170.6°F), the chiller's capacity is greater than 60% of its rated capacity as determined by the generator inlet and cooling tower return temperatures, and the capacity is sufficient to meet the load. Otherwise, valve V-1 bypasses the solar storage and auxiliary energy is obtained from the offpeak hot water storage. Offpeak storage is sized so that no electric energy except that required by pumps and fans is used during the on-peak period.

The system shown in Figure B-23 utilized offpeak chilled water storage to minimize the use of electricity during on-peak periods. The minimum allowable inlet temperature to the absorption chiller's evaporator is 8°C (46.4°F). The maximum usable chilled water temperature is 15.6°C (60°F). These temperatures define the usable temperature range for the chilled water storage. As with the system shown in Figure B-21, the operation of the absorption chiller is controlled based on the temperature in the chilled water storage tank. If the temperature in the solar storage tank is greater than 77°C (170.6°F) and the temperature in the chilled water tank is greater than 8°C (46.4°F), the solar air conditioner uses thermal energy from solar storage to reduce the temperature in the chilled water storage. The chilled water storage tank is sized so that at half capacity the entire load for an on-peak period can be met. That is, if the temperature in the chilled water storage tank is less than 11.8°C (53.2°F) at the start of an on-peak period, the auxiliary electric heater will not be required during the period. Consequently, during each offpeak period valve V-1 bypasses solar storage and the auxiliary electric heater is used to fire the absorption chiller when the chilled water temperature is greater than 11.8°C (53.2°F). The chiller runs until the chilled water temperature is decreased below this temperature. Chilled water is pumped through the duct mounted cooling coil whenever the space thermostat calls for cooling.

B.6 REFERENCES

B-1. Specification CTS769-777, Fedders Corporation, Edison, New Jersey, 08817.

B-2. Bulletin 216-B-131A, American Air Filter Co., Inc., Louisville, Kentucky.

B-3. Private communication with John Kittredge, Philadelphia Electric Company, August 3, 1978.

B-4. Private communication with Frank Smith, Long Island Lighting Company, November 8, 1978.

B-5. Ward, D.S., Uesaki, T. and Löf, G.O.G., "Cooling Subsystem Design in CSU Solar House III," Proceedings of the 1976 Joint Conference, American Section, International Solar Energy Society and the Solar Energy Society of Canada, Inc., Winnipeg, Vol. 3, August 1976.

APPENDIX C

ABSORPTION CHILLER MODEL

C.1 INTRODUCTION

An absorption chiller model was developed for the performance simulation of solar air conditioning systems. The model was developed to be compatible with the TRNSYS computer program and to simulate the performance of machines with either air or liquid cooled evaporators. The effect of transient delays associated with the startup of absorption machines was included in the model. For chillers with either an air cooled or liquid cooled evaporator the model calculates performance using empirical relationships developed from manufacturers' data.

When the analyses of solar absorption air conditioning systems were performed, the latest version of TRNSYS (Version 9.2) had a simple absorption chiller model. For the purposes of this study, a more versatile model was created. A new version of TRNSYS (10.0) is now available which contains a more sophisticated absorption chiller model which includes a detailed treatment of startup transients and their effect on performance.

C.2 ABSORPTION CHILLER WITH AIR COOLED EVAPORATOR

This model is a modified version of the absorption air conditioner model described in Reference C-1 and included in TRNSYS up to version 10.0. It approximates the performance of an Arkla DUCS-2 lithium-bromide machine.

The cooling capacity of the chiller is determined as a function of the generator hot water inlet temperature and the return water temperature from the cooling tower within the limits of 0.6 to 1.1 times the rated capacity. It is assumed that the cooling tower can reduce the temperature of the warm water from the condenser to the ambient wet bulb temperature plus 5.6°C (10.1°F), but not less than 10°C (18°F). The minimum allowable generator temperature is 77°C (170.6°F). The capacity of the machine can be specified. When the specified capacity is different from that of the Arkla unit on which the model is based (i.e., 37,970 kJ/hr or 3 tons), generator, condenser and evaporator flow rates are adjusted by the ratio of the specified capacity to that of the Arkla unit. When the cooling load is less than the machine's capacity as determined by the generator and condenser inlet temperatures, the model assumes that the unit is modulated so that the cooling load is just met. This capability to modulate capacity to meet the load was not available with the DUCS-2 machine. However, Arkla's new Solaire 36P air conditioner includes a generator by-pass valve for load matching to minimize cycling and improve performance (Ref. C-2). The TRNSYS model assumes that if the temperature of the water from solar storage is too low for the air conditioner to meet the load, that the thermal input to the generator is supplied entirely by an auxiliary system. The TRNSYS model was modified so that the auxiliary system could be disabled when desired.

The steady state coefficient of performance (COP) of the absorption unit is 0.68 and the thermal input to the generator is calculated as the cooling load divided by the COP.

An absorption chiller requires several pumps and fans including hot and chilled water pumps, a condenser water pump and a cooling tower fan. The electricity usage by these auxiliary devices can be large enough to have a significant effect on system feasibility. The auxiliary electric energy requirements for a 3 ton chiller were estimated to be 0.75 kW based on equipment data presented in Reference C-2. The capability of calculating electricity usage by pumps and fans was included in the model.

C.3 ABSORPTION CHILLER WITH A LIQUID COOLED EVAPORATOR

The Arkla DUCS-2 absorption chiller has, in fact, a liquid cooled evaporator. However, the empirical relationships used to model its performance were developed assuming the evaporator was connected to a fan coil unit by means of a water transfer loop. Thus, in effect this model assumes that the evaporator is air cooled. A new model was developed for the simulation of absorption cooling systems with chilled water storage. In this model, the absorption chiller's performance is evaluated as a function of the evaporator inlet temperature in addition to the inlet temperatures to the generator and condenser.

The empirical relationships used in the model were derived from performance data for the Yazaki Corporation Model No. WFC-600S lithium-bromide absorption chiller as presented in Reference B-5. This machine is rated at 2,100 kJ/hr (2.2 tons). The steady state COP is calculated as a function of the generator inlet temperature (T_g) and the evaporator inlet temperature (T_e) as shown in the following equation:

$$COP = A\ (M) + A_1(M) \times T_g + A_2(M) \times T_e$$

and:

$$\begin{aligned} M &= 1 \text{ when } 8 \le T_e \le 10.5 \\ &= 2 \text{ when } 10.5 < T_e \le 13.5 \\ &= 3 \text{ when } 13.5 < T_e \le 16.5 \\ &= 4 \text{ when } T_e > 16.5 \end{aligned}$$

For each interval of evaporator inlet temperature, A_0, A_1 and A_2 are constants. The maximum COP is 0.68. In a similar manner, the ratio of actual to rated capacity (CAP_r) is calculated as follows:

$$CAP_r = [B_0(M) + B_1(M) \times T_g + B_2(M) \times T_e] \times D_1 \times D_2$$

where:

$D_1 = 1.1469 + 0.002966\ T_g - 0.0221129\ T_{wb}$

$D_2 = 0.001532\ \mathrm{Exp}[0.0747\ T_g]$

T_{wb} = ambient wet bulb temperature

B_0, B_1, B_2 = constants for each interval of evaporator inlet temperature

The values of constants A_0-A_2 and B_0-B_2 are listed in Table C-1

Table C-1. Chiller Parameters

	M = 1	M = 2	M = 3	M = 4
A_0	-2.19197	-1.8493	-0.9347	0.68
A_1	0.0325	0.021	0.01104	0.0
A_2	0.0699	0.055	0.04525	0.0
B_0	-3.918	-3.4787	-1.979	-0.54
B_1	0.04773	0.04427	0.0304	0.0186
B_2	0.082	0.068	0.039	0.009

The minimum allowable generator inlet and evaporator inlet temperatures are 77°C (170.6°F) and 8°C (46.4°F), respectively. At the Yazaki unit's rated capacity the generator flow rate is 1682 kg/hr (3700 lb/hr) and the condenser flow rate is 1205 kg/hr (2650 lb/hr). The capacity can range between 0.2 and 1.35 times the rated capacity. When a machine capacity different from that of the Yazaki unit is specified, the model adjusts the generator and evaporator flow rates accordingly. As with the model described previously, the electricity usage by auxiliary pumps and fans is calculated.

C.4 ABSORPTION CHILLER STARTUP TRANSIENTS

The coefficient of performance (COP) of an absorption chiller under steady-state operating conditions is in the range of 0.6 to 0.7. However, it has been found that the seasonal COP may be much lower. This is due in part to the startup transients of absorption chillers. When an absorption chiller is started, there is a delay between the time startup is initiated and cooling begins. Once cooling begins, the machine may require an hour or more to reach its steady-state COP. The startup transients are due to the complex nature of the absorption cooling machine. Time is required for the generator to come up to operating temperature and for the refrigerant and absorbent fluids to become heated and begin circulating. There are also transients associated with the cooling tower and the heating up of pipes and other fluids that may be included in the system. If the cooling load is such that the machine cycles on and off with any regularity, the steady-state COP may never be reached and performance will suffer. Since the steady-state COP of absorption chillers is much lower than vapor compression chillers (0.6 vs. 2.5-3.5) it is important that cycling of the absorption machine be minimized. One of the objectives of this study was to investigate methods by which cycling of solar absorption cooling systems could be reduced by use of hot and/or cold storage to match the operating characteristics of the absorption chiller to the load and the availability of solar energy. Consequently, the effects of startup transients were incorporated in the computer model.

The effect of startup transients on absorption chiller performance is shown in Figure C-1 (Ref. B-5). Initially, as the length of the operating period increases, the average COP increases rapidly. For operating periods greater than 30 minutes, the COP increases less rapidly and gradually approaches the steady-state COP.

The TRNSYS computer program employs hourly weather data but generally in system simulations, calculations are performed at intervals of time (time steps) which are less than one hour (i.e., one-quarter or one-eighth of an hour). The length of the time step is chosen based on a compromise between the required accuracy of the results and computer time. A further consideration is that the time step must be sufficiently small that the stability conditions for the TRNSYS numerical integration algorithm be satisfied. For systems considered in this study, it was found that a time step of one-quarter or one-eighth of an hour were sufficient. Generally, it was found that if a system had one storage tank, a time step of one-quarter hour was acceptable. When two tank systems were simulated, it was necessary to use a time step of one-eighth hour.

The approach used to incorporate the effect of startup transients into the absorption chiller model is shown in Figure C-2. The smooth

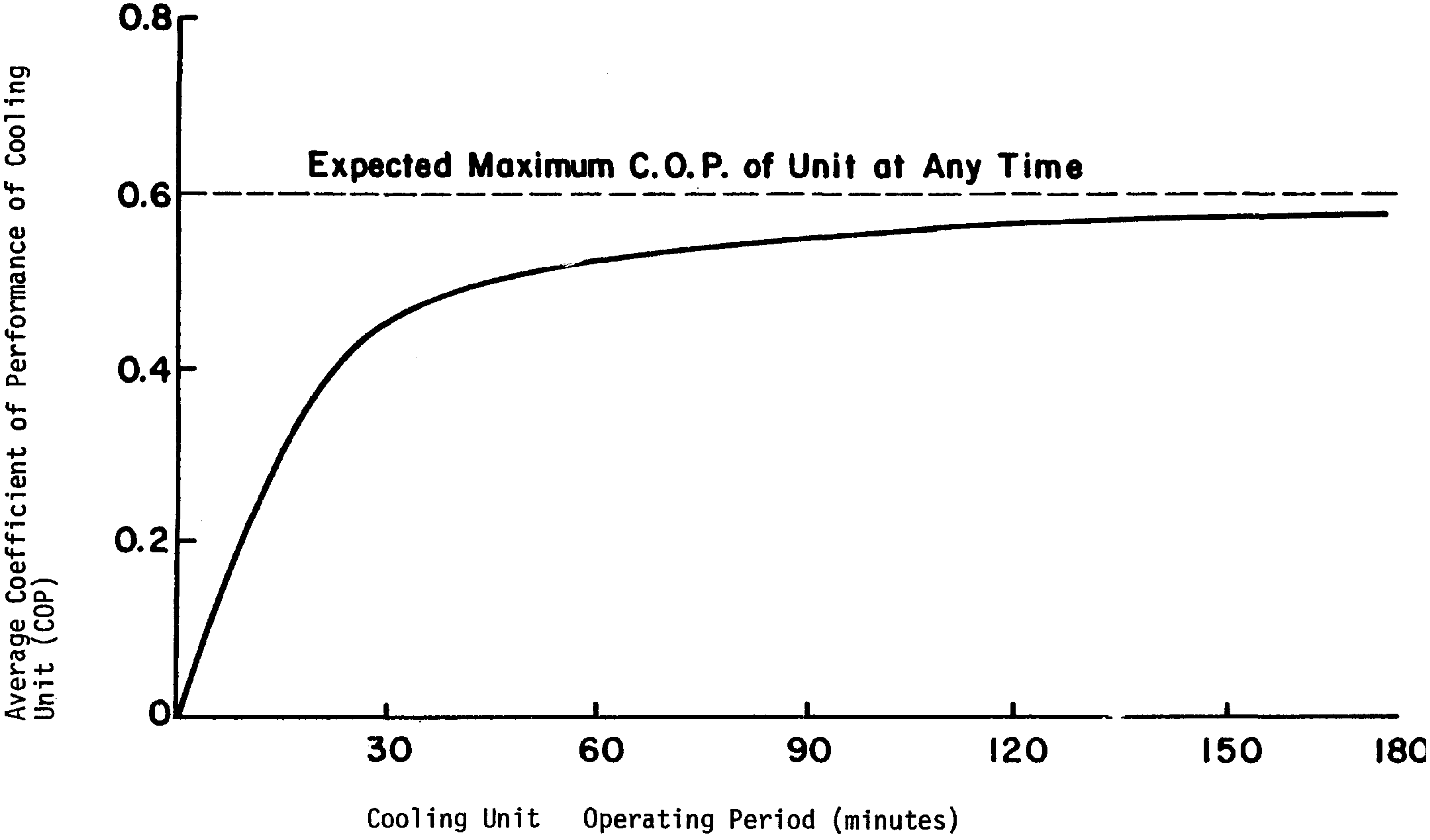


Figure C-1. Average COP vs. Cooling Unit Operating Period

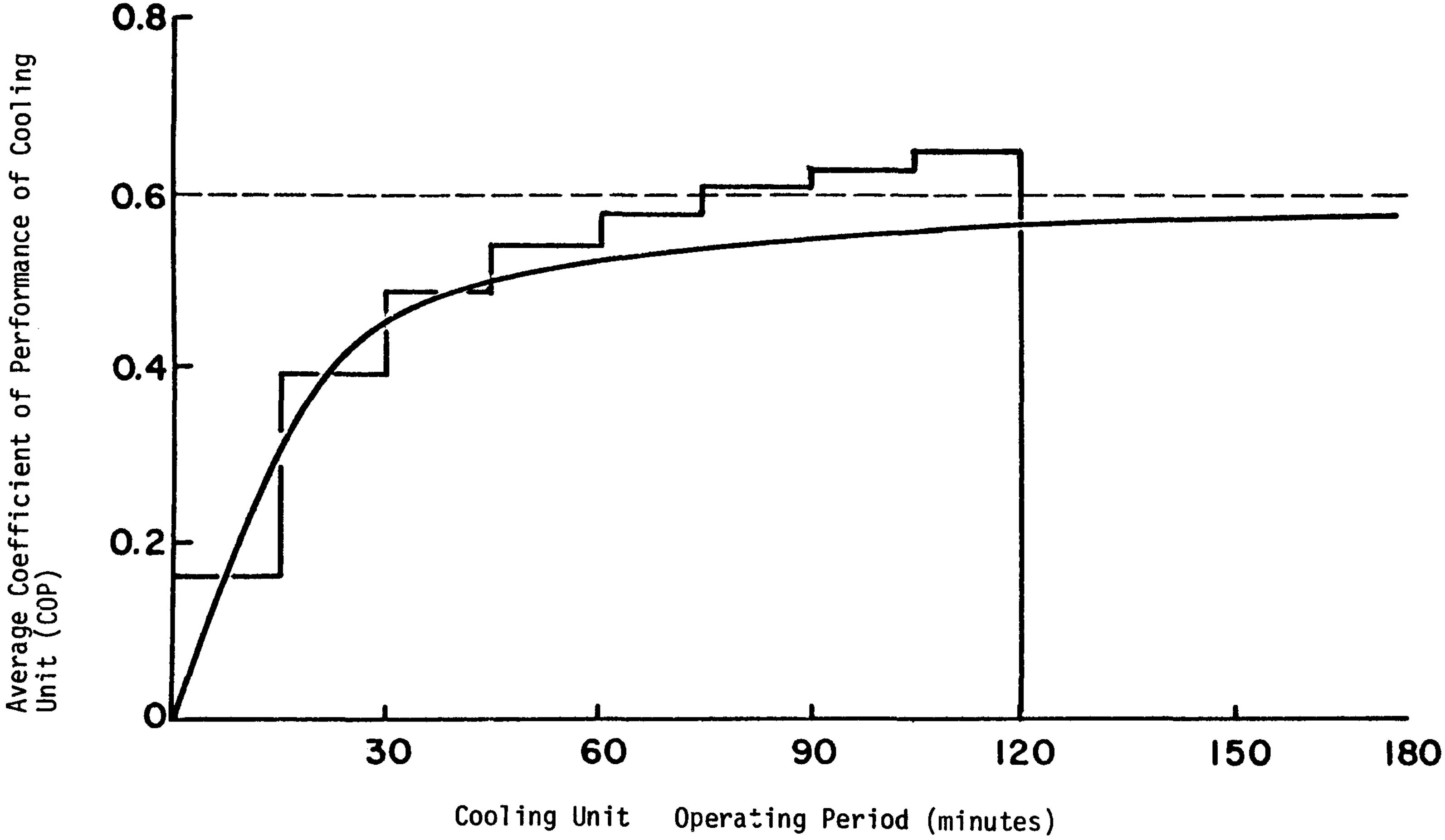


Figure C-2. Average COP vs. Cooling Unit Operating Period curve in Figure C-2 is repeated from Figure C-1. The stepped curve in Figure C-2 represents the COP for each 15 minutes (one-quarter of an hour) that the absorption chiller operates. For example, if the chiller has been inoperative, for the first 15 minutes the COP would be 0.16, for the next 15 minutes it would be 0.39 and after two hours of operation the COP would equal the steady-state value of 0.68. The model monitors the length of time the chiller has been operating and increases the COP for each succeeding time step until the steady-state COP is reached. A similar stepped curve was developed for systems which required the use of a one-eighth hour time step in TRNSYS simulations.

In the cooling system simulations performed, a standard set of hourly cooling loads were used. These loads were calculated once and then used for each simulation. This approach conserves computational effort but the simulation system-load interaction is less realistic. In the approach used, a constant cooling load is assumed to exist for an entire hour, whereas it's possible that the load may have fluctuated or existed for only part of the hour and caused the absorption chiller to cycle. However, this deficiency in the use of standardized cooling loads is mitigated to some extent when the absorption chiller has a means of modulating capacity (i.e., a generator bypass) as was assumed for this study.

C.5 PRELIMINARY ANALYSES

Initial studies were performed to determine the effect of various system and simulation model variables on calculated system performance. An important consideration for a proposed solar air conditioning system is the type of solar collector to be used. Three types of flat plate solar collectors were evaluated: a double-glazed collector with a flat black absorber surface, and single and double-glazed collectors with a black chrome selective absorber surface. Performance curves for these collectors were derived from performance data for Revere Copper and Brass Inc. "SUN-AID" modular solar energy collectors (Ref. C-3). The performance curves are as follows:

$$\text{Double-Glazed Flat Black} \qquad \eta = 0.686 - 20.478 \frac{(T_i - T_a)}{I}$$

$$\text{Single-Glazed Selective Black} \qquad \eta = 0.694 - 18.360 \frac{(T_i - T_a)}{I}$$

$$\text{Double-Glazed Selective Black} \qquad \eta = 0.622 - 13.319 \frac{(T_i - T_a)}{I}$$

where: η = collector efficiency
T_i = collector inlet temperature (°C)
T_a = ambient temperature (°C)
I = incident radiation ($\text{kJ/hr-m}^2\text{-°C}$)

The performance of a conventional solar air conditioning system (refer to Figure B-A) employing each of these collectors was simulated using Philadelphia weather data. For these, and all other solar air conditioning system analyses the collectors were assumed to face due South and be tilted at an angle equal to the latitude minus 15°. The collector area was 37.2 m^2 (400 ft^2) and the size of solar storage was equivalent to 81.5 kg/m^2 (2 $gallons/ft^2$) of collector area. The significant simulation results are shown in Table C-2.

Table C-2. Effect of Collector Type on the Performance of a Conventional Solar Air Conditioner

Collector Type	Solar Fraction	Collector Efficiency	SPF	SPF_e
Double-glazed, flat black	0.524	0.167	0.677	1.436
Single-glazed, selective	0.627	0.197	0.677	1.815
Double-glazed, selective	0.711	0.224	0.677	2.347

The solar fractions as shown in Table C-2 are defined as follows:

$$\text{Solar Fraction} = 1 - \frac{\text{(auxiliary energy use)}}{\left\{\begin{array}{l}\text{absorption chiller's} \\ \text{thermal energy demand}\end{array}\right\}}$$

The collector efficiency is the ratio of the usable output from the collectors to the total incident solar radiation. The seasonal performance factor (SPF) is the ratio of the seasonal cooling load to the total thermal input to the absorption chiller's generator. The factor SPF_e is the ratio of the seasonal cooling load to the total electric energy usage and indicates the extent to which solar energy replaces purchased energy. By comparison, a vapor compression air conditioner would have an SPF_e in the range of 2.2 to 3.0. While the double-glazed collector with a selective absorber surface is shown in Table C-2 as having the best performance in this application, for most of the solar air conditioning system simulations performed in this study, a single-glazed, selective collector was used. The use of double-glazed, selective collectors in solar space and/or domestic water heating applications is rare. Since combination solar heating and cooling systems were being studied in addition to systems capable of only heating or cooling, it was decided to use a single collector type which was compatible with all systems to facilitate a comparison of results.

It can be seen in Table C-2 that the seasonal performance factor (SPF) in all cases is 0.677 which is essentially the same as the absorption chiller's steady-state COP. This occurred because, as described in Subsections C.2 and C.3, the model assumes that the chiller capacity is modulated so that the load can be met without on/off cycling of the chiller. As described in Subsection C.4, hourly cooling loads were calculated on an hourly basis such that a constant load was assumed to exist for each hour. This method of calculating loads in combination with the assumption that chiller capacity can be effectively modulated minimizes the time that the chiller is inoperative. Thus, startup transients as treated by the chiller model do not have a significant impact on the SPF.

The TRNSYS computer program is capable of treating water storage as a fully mixed or as thermally stratified. Thermal stratification is modelled by assuming that the tank consists of several fully-mixed equal volume segments. Thermal stratification may be particularly effective in solar air conditioning system solar or offpeak hot storage where the minimum usable temperature is 77°C (170.6°F). However, simulating stratified thermal storage as compared to fully-mixed storage using TRNSYS increases the computational effort because an additional differential equation must be solved for each degree of stratification (i.e., the number of fully-mixed segments into which the storage tank is divided). The effect of thermal stratification versus the use of a fully-mixed storage on the performance of a conventional solar air conditioner was tested. The results are shown in Table C-3 for two types of collectors. In each case, the collector area was 37.2 m^2 (400 ft^2), the storage size was equivalent to 81.5 Kg/m^2 (2 $gallons/ft^2$) of collector area, the storage tanks were assumed to have a height to diameter ratio of 4, and the stratified storage was divided into three equal volume segments.

Table C-3. Effect of Storage Thermal Stratification on Solar Air Conditioning System Performance

	Stratified Storage				Fully Mixed Storage			
Collector Type	Solar Fraction	Collector Efficiency	COP	COP_e	Solar Fraction	Collector Efficiency	COP	COP_e
Single-Glazed, Selective	0.627	0.197	0.677	1.814	0.605	0.191	0.677	1.716
Double-Glazed, Selective	0.711	0.224	0.677	2.347	0.696	0.219	0.677	2.225

It can be seen that thermal stratification of storage results in a modest improvement in system performance, mainly because the average inlet temperature to the solar collectors is reduced slightly. The type of collector used has a more significant effect. Consequently, it was decided that the increase in performance resulting from thermal stratification did not justify the additional simulation time and cost. All future simulations were performed assuming storage was fully mixed.

The conventional solar air conditioner uses electricity on demand when the temperature in the thermal storage tank is too low. This may occur during on or offpeak periods. Assuming a rated capacity of 25,310 kJ/hr (2 tons), an electrically fired absorption chiller operating at full capacity and at its steady-state COP (0.68) would have a demand of 10.3 kW excluding pump and fan power requirements. By comparison, a vapor compression air conditioner would have a demand of 2.4 kW assuming a COP of 2.9. Obviously, the use of electricity to fire an absorption chiller, particularly during on-peak periods, could have a major impact on a utility's peak demand. Generally, however, the chiller will be operating at less than its rated capacity and the impact on the utility will be less severe. The effect of collector area on peak electric demands for a conventional solar air conditioner as compared to the peak demands for a conventional vapor compression air conditioner was investigated. It was assumed that as collector area was increased for a given capacity of absorption chiller that the solar fraction would increase and therefore the probability of occurrence and the magnitude of on-peak electric demands would be reduced. Systems were simulated using Philadelphia weather data for 1968. Collector areas of 37.2 m^2 (400 ft^2), 55.8 m^2 (600 ft^2) and 74.3 m^2 (800 ft^2) were considered. In each case storage was assumed to be fully mixed and to be sized equivalent to 81.5 kg/m^2 (2 gallons/ft^2) of collector area. The results are shown in Table C-4. It can be seen, that as collector area is increased the solar absorption system's overall coefficient of performance (COP) and the coefficient of performance relative to electric energy use (COP_e) increase and that the maximum on-peak electric demand and seasonal electric usage decrease. The collector efficiency also decreases. The largest solar system has both a lower peak demand and seasonal electric use than the vapor compression system. The 0.46 kW demand for the largest solar system represents the power requirements by pumps and fans. For this system, the absorption chiller never used the electric auxiliary system during the on-peak period.

Table C-4. Comparison of the Performance of Conventional Solar and Vapor Compression Air Conditioners

System	Collector Area* m^2 *ft^2)	Collector Efficiency	COP	COP_e	Seasonal On-Peak Electric Demand (kW)	Seasonal Electric Energy Use (kWh)
Solar A/C	37.2(400)	0.196	0.647	1.386	4.89	3422
	55.8(600)	0.172	0.666	2.266	4.50	2093
	74.3(800)	0.150	0.672	3.644	0.46	1301
Vapor Compression A/C	-	-	-	2.9	1.9	1578

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*Single-Glazed, Selective

Based on the results shown in Table C-4, it would appear that the largest system would be of significant benefit in decreasing utility peak loads. However, from a practical standpoint, the collector area is too large to mount on the roof of the house for which the cooling loads were calculated. This house has a usable roof area of 40.9 m^2 (440 ft^2) as compared to the collector area of 74.3 m^2 (800 ft^2) of the largest solar system in Table C-4. It has been assumed in this study that a method could be found to mount up to 55.8 m^2 (600 ft^2) of collector area on this house but the installation of a system with 74.3 m^2 (800 ft^2) would be impractical.

C.6 REFERENCES

C-1. Butz, L.W., Beckman, W.A., and Duffie, J.A., "Simulation of a Solar Heating and Cooling System," Solar Energy, 16, 129 (1974).

C-2. Solaire 36P, Arkla Industries Form No. SA-41240, April, 1978.

C-3. Private communication with Mr. William Denny, Applied Solar Products, Havertown, PA, May, 1977.

APPENDIX D

INSTALLED SYSTEM CAPITAL COSTS

D-1. INFORMATION SOURCES

Installed costs were estimated for all systems that were submitted to the electric utilities for analysis. These costs reflect estimated equipment and labor costs for December 1979. In certain instances, prices which were obtained prior to December 1979 were adjusted to account for inflation up until that date.

Most of the equipment and labor costs were obtained from the 1979 Dodge Manual (Ref.D-1). Solar collector costs were obtained from a national manufacturer (Ref. D-10). Installed costs for conventional air-to-air and water-to-air heat pumps were obtained from Christian (Refs. D-2, D-3) while estimated costs for dual source heat pumps and absorption air conditioners were obtained from several commercial sources (Refs. D-4, D-5, D-6). Installed costs for conventional cooling and hot water heating equipment were also obtained from commercial sources (Refs. D-7, D-8). A local manufacturer (Ref. D-9) supplied the cost of immersion heating coils for off-peak energy storage.

All of the systems in this study, both conventional and solar, were assumed to use air ducts to supply hot or cold air throughout the residence. Therefore the cost of this ducting system was not included in any of the total system costs presented here.

D-2. HEATING SYSTEMS FOR PHILADELPHIA AND COLUMBUS

Base System - Forced Air with a Resistance Space Heating Coil in the Duct

All systems have duct work and this cost is not included in any of the systems.

	Material	Labor
Electric Duct Heater - 10 kW	$ 362.50	$ 67.80
Air Conditioner, Vapor Compression, 2-Ton	1200.00	300.00
	$1562.50	$367.80

Total Cost $1930

Resistance Space Heating with Off-Peak Storage

	Material	Labor
Electric Duct Heater, 10 kW	$ 362.50	$ 67.80
Duct Hot Water Coil	217.00	352.35
Insulated Hot Water Tank 2.77 m^3 (750 gal)	2300.00	300.00
Electric Water Heating Coil, 36 kW	900.00	300.00
Water Pump, 1/6 hp	255.00	126.80
Copper Pipe - 20 ft - 1-1/2"	57.80	89.20
Pipe Insulation - 20 ft	24.80	39.00
Pressure Relief Valve - 1-1/2"	15.47	10.57
Isolation Valves (Gate) - 1-1/2" (2)	53.92	26.32
Air Conditioner, Vapor Compression, 2-Ton	1200.00	300.00
Offpeak Timer	25.00	15.00
	$5415.00	$1682.00
Total Cost	$7097	

Conventional Solar Space Heating System

	Material	Labor
Solar Collectors, 41.8 m^2 (450 ft^2)	$6050.15	$ 999.02
Pump (collector) 1/5 hp	343.70	142.70
Differential Controller	88.00	40.14
Sensors (2)	18.00	32.10
Isolation Valves (4)	63.16	35.08
Balancing Valves - 1" (2)	34.74	17.54
Balancing Valves - 3/4" (2)	26.36	16.62
Pressure Relief Valve	15.50	10.57
Vacuum Breaker	17.50	15.79
Strainer	11.34	15.85
Expansion Tank	215.25	190.27
Check Valve	13.44	8.77
Storage Tank, 3.35 m^3 (900 gal) Insulated	1933.00	400.00
Copper Pipe - 1" (120 ft)	219.60	472.80
Pipe Insulation (120 ft)	124.80	223.20

Conventional Solar Space Heating System (Cont'd)

	Material	Labor
Mounting Hardware	$ 832.00	$ 684.32
Pump (load)	255.00	126.80
Duct Hot Water Coil	217.00	352.35
Start up + Balancing		157.92
Copper Pipe, 1-1/2" - 20 ft	57.80	84.20
Pipe Insulation - 20 ft	24.80	39.00
Insolation Valves (2)	53.92	26.32
	$10,915.00	$4391.00
Total Cost	$15,306	

Total Costs for the Conventional Solar System include cost of the back-up resistance heating coil in the hot air duct.

	Material	Labor
Solar System, 41.8 m^2 (450) collectors, 3.35 m^3 (900 gal) storage	$10,915.00	$4391.00
Electric Duct Heater, 10 kW	362.50	68.70
Air Conditioner, Vapor Compression, 2-Ton	1200.00	300.00
	$12,477.50	$4759.70
Total Cost	$17,237	

Solar System with Separate Off-Peak Storage

Solar System cost is identical to conventional solar system.

	Material	Labor
Solar System, 41.8 m^2 (450 ft^2) collectors, 3.35 m^3 (900 gal) storage	$10,915.00	$4391.00
Storage Tank (Off-Peak 2.77 m^3 (750 gal) insulated	2300.00	360.00
Solenoid Valves (2)	508.00	128.44
Immersion Heater, 36 kW	900.00	300.00
Off-Peak Timer	25.00	15.00
Thermostat (for choosing proper tank)	77.00	26.40
Air Conditioner, Vapor Compression, 2-Ton	1200.00	300.00
	$15,925.00	$5521.00
Total Cost	$21,446	

Conventional Heat Pump, Air to Air Unitary, 2 ton

	Material	Labor
Cost	$1150	$1272
This includes two 4.8 kW resistance heaters, and total installation		
Total Cost	$2422	

Heat Pump w/Off-Peak Storage

	Material	Labor
Heat Pump, Dual Source, 2-Ton	$1800.00	$1280.00
Off-Peak Timer	25.00	15.00
Storage Tank (Off-Peak), 7.43 m^3 (200 gal)	4335.00	1000.00
36 kW Immersion Heater	900.00	300.00
	$7060.00	$2595.00
Total Cost	$9655	

Solar Assisted Heat Pump

	Material	Labor
Solar System, 41.8 m^2 (450 ft^2) collector 3.35 m^3 (900 gal) storage, and excluding duct hot water coil	$10,915.00	$4391.00
Heat Pump, Water-to-Air, 2-Ton	1000.00	852.00
	$11,915.00	$5243.00
Total Cost	$17,158	

Solar Assisted Heat Pump with Off-Peak Storage in the Solar Storage Tank

	Material	Labor
Solar Assisted Heat Pump System Minus the Electric Duct Heater	$11,905.00	$5,034.00
Off-Peak Timer	25.00	15.00
Immersion Heater, 36 kW	900.00	300.00
	$12,830.00	$5,349.00
Total Cost	$18,179	

Solar Assisted Dual Source Heat Pump with Direct Heating from Solar

	Material	Labor
Conventional Solar Energy System, 41.8 m^2 (450 ft^2) collector, 3.35 m^3 (900 gal) storage	$10,915.00	$4391.00
Heat Pump, Dual Source, 2-Ton	1800.00	1280.00
Solenoid Valves, 1-1/2" (2)	508.00	124.44
Controls	200.00	100.00
	$13,423.00	$5895.44
Total Cost	$19,318	

Solar Assisted Dual Source Heat Pump with Direct Heating and Off-Peak Storage in the Solar Storage Tank

	Material	Labor
Conventional Solar Energy System, 41.8 m^2 (450 ft^2) collector, 3.35 m^3 (900 gal) storage, minus 10 kW electric duct heater	$11,298.00	$4427.00
Heat Pump, Dual Source, 2-Ton	4000.00	2000.00
Off-Peak Timer	25.00	15.00
Immersion Heater, 36 kW	900.00	300.00
	$16,223.00	$6742.00
Total Cost	$22,865	

Solar Assisted Dual Source Heat Pump with Direct Heating and a Separate Off-Peak Storage Tank

	Material	Labor
Solar Heating System, 41.8 m^2 (450 ft^2) collectors, 3.35 m^3 (900 gal) storage, minus 10 kW electric duct heaters	$11,298.00	$4427.00
Heat Pump, Dual Source, 2-Ton	4000.00	2000.00
Storage Tank, Off-Peak, 3.35 m^3 (900 gal) Insulated	2943.00	846.00
Immersion Heater, 36 kW	900.00	300.00
	$19,141.00	$7,573.00
Total Cost	$26,714	

Solar Air Conditioning with 55.7 m^2 (600 ft^2) Collection System

	Installed Cost
Solar Heating System, 55.7 m^2 (600 ft^2) collectors, 4.46 m^3 (1200 gal) storage, @ \$361.15/m^2(\$34.01/ft^2)	\$20,408.00
Air Conditioner, Absorption, 2-Ton Package with all Necessary Hardware	7000.00
Total Cost	\$27,408.

Solar Air Conditioning with Off-Peak Cold Storage and Hot Storage for Heating

	Installed Cost
Solar Heating System, 55.7 m^2 (600 ft^2) collectors, 4.46 m^3 (1200 gal) storage, @ \$361.15/m^2(\$34.01/ft^2)	\$20,408.00
Storage Tank (Off-Peak), 2.77 m^3 (750 gal), Insulated	2660.00
Immersion Heater, 36 kW	1200.00
Storage Tank (Off-Peak), 6.32 m^3 (750 gal)	3240.00
Off-Peak Timer and Thermostat	150.00
Air Conditioner, Absorption, 2-Ton Package with all Necessary Hardware	7000.00
Total Cost	\$34,650.

Solar Air Conditioning with Off-Peak Hot Storage, (2 Tanks) and Off-Peak Hot Storage for Heating

	Installed Cost
Solar Heating System, 55.7 m^2 (600 ft^2) collectors, 7.44 m^2 (1200 gal) storage, @ \$361.15/m^2(\$34.01/ft^2)	\$20,408.00
Storage Tank, (Off-Peak) 2.77 m^3 (750 gal), Insulated	2660.00
Immersion Heater, 36 kW	1200.00
Air Conditioner, Absorption, 2-Ton Package with all Necessary Hardware	7000.00
Total Cost	\$31,420

D-3. HEATING SYSTEMS FOR DAYTONA BEACH

Resistance Space Heating

	Material	Labor
Electric Duct Heater, 75 kW	$ 330.00	$ 64.20
2-1/2 Ton Air Conditioner	1500.00	375.00
	$1830.00	$439.20
Total Cost	$2269.	

Resistance Water Heating

	Material	Labor
Water Heater, 0.22 m^3 (60 gal), 2-element	$ 203.80	$126.30
Mixing Valve	14.95	15.00
	$ 218.75	$141.30
Total Cost	$360.	

Resistance Water Heating with Off-Peak Storage

	Material	Labor
Water Heater, 0.45 m^3 (120 gal) 2-element	$ 310.60	$192.50
Off-Peak Timer	25.00	15.00
Mixing Valve	14.95	15.00
	$ 350.55	$222.50
Total Cost	$573.	

Conventional Solar Space Heating

	Material	Labor
Solar Collector, 9.66 m^2 (104 ft^2)	$1400.00	$256.60
Collector Pump, (1/12 hp)	97.00	52.64
Differential Controller	88.00	40.14
Sensors (2)	18.00	32.10
Isolation Valves, 3/4"	25.20	16.62
Pressure Relief Valve, 3/4"	15.50	10.57

Conventional Solar Space Heating (Cont'd)

	Material	Labor
Vacuum Breaker	$ 11.23	$ 15.79
Strainer	9.40	13.21
Expansion Tank 0.06 m^3 (15 gallon)	215.25	190.27
Check Valve	10.16	8.31
Storage Tank 0.77 m^3 (206 gal) Insulated	730.00	250.00
Copper Tubing, 3/4", 80 ft	112.80	252.00
Pipe Insulation, 3/4", 80 ft	80.00	140.00
Mounting Hardware	160.00	131.60
Load Pump, 1/12 hp	97.00	52.64
Duct Hot Water Coil	170.00	264.26
Copper Tubing, 1/2", 20 ft	24.00	52.60
Tubing Insulation, 1/2", 20 ft	18.00	35.00
Start-up and Balancing	-	157.92
2-1/2-Ton Air Conditioner	1500.00	375.00
Electric Duct Heater, 7.5 kW	330.00	64.20
	$5111.54	$2411.47
Total Cost	$7523.	

Conventional Solar Water Heating

	Material	Labor
Solar Collectors, 3.88 m^2 (41.8 ft^2)	$ 562.70	$ 103.10
Collector Pump, 1/60 hp	74.00	36.00
Differential Controller	88.00	40.14
Sensors (2)	18.00	32.10
Vacuum Breaker	11.23	15.79
Strainer	9.40	13.21
Isolation Valves	17.60	11.60
Pressure Relief Valve	10.85	7.50
Check Valve	10.16	8.31
Copper Tubing	96.50	209.75
Tube Insulation	71.76	133.70

Conventional Solar Water Heating (Cont'd)

	Material	Labor
Mounting Hardware	$ 64.30	$ 52.90
Storage Tank, 0.22 m^3 (60 gal), Insulated	174.15	107.70
Water Heater, 0.28 m^3 (75 gal), 2-element	276.80	171.70
Mixing Valve	14.95	15.00
	$1500.40	$958.50
Total Cost	$2459.	

Solar Water Heating with Off-Peak Storage

Cost identical to conventional solar water heating system with the addition of an off-peak timer.

	Material	Labor
Solar Water Heating System	$1500.40	$958.50
Off-Peak Timer	25.00	15.00
	$1525.40	$973.50
Total Cost	$2499.	

Resistance Space Heating with Off-Peak Storage

	Material	Labor
Electric Duct Heater 7.5 kW	$ 330.00	$ 64.20
Duct Hot Water Coil	170.00	264.26
Insulated Hot Water Tank (350 gal)	1150.00	429.00
Immersion Heater, 25 kW	660.00	225.00
Pump (collector), 1/12 hp	95.00	52.64
Copper Pipe, 20 ft, 1/2"	24.00	52.60
Pipe Insulation, 20 ft, 1/2"	18.00	35.00
Isolation Valve	10.32	15.78
Off-Peak Timer	25.00	15.00
Pressure Relief Valve	6.60	10.57
2-1/2 Ton Air Conditioner	1500.00	375.00
	$3988.92	$1539.05
Total Cost	$5528.	

Solar Air Conditioning with 55.7 m^2 (600 ft^2) Collection Area

		Installed Cost
Solar Heating System, 55.7 m^2 (600 ft^2) of collectors 4.5 m^3 (1200 gal) storage, @ \$366.12/m^2 (\$34.01/ft^2)		\$20,408.00
2-1/2 Ton Absorption Air Conditioning Package		8,500.00
	Total Cost	\$28,908.

Solar Air Conditioning with Off-Peak Hot Storage

		Installed Cost
Solar Heating System, 55.7 m^2 (600 ft^2) of collectors 4.5 m^3 (1200 gal) storage, @ \$366.12/m^2(\$34.01/ft^2)		\$20,406.00
2-1/2 Ton Absorption Air Conditioning Package		8,500.00
Storage Tank (Off-Peak), 3.5 m^3 (950 gal) Insulated		3,700.00
Immersion Heater, 17.5 kW		650.00
Off-Peak Timer		40.00
	Total Cost	\$33,296.

D-4. HEATING SYSTEMS FOR SAN DIEGO

Resistance Space Heating

	Material	Labor
Electric Duct Heater, 5-kW	\$ 268.00	\$ 53.50
2-Ton Air Conditioner	1200.00	300.00
	\$1468.00	\$353.50
Total Cost	\$1822.	

Resistance Space and Hot Water Heating

	Material	Labor
Electric Duct Heater, 5-kW	\$ 268.00	\$ 53.50
Water Heater, 0.22 m^3 (60 gal), 2-element	203.80	126.30
Mixing Valve	14.95	15.00
2-Ton Air Conditioner	1200.00	300.00
	\$1686.75	\$ 494.80
Total Cost	\$2182.	

Resistance Space Heating with Off-Peak Storage

	Material	Labor
Electric Duct Heater, 5-kW	$ 268.00	$ 53.52
Duct Hot Water Coil	170.00	264.26
Storage Tank (Off-Peak) 0.929 m^3 (250 gal) Insulated	885.00	300.00
Immersion Heater, 15 kW	440.00	150.00
Pump, 1/12 hp	95.00	52.64
Copper Pipe, 1/2", 20 ft	24.00	52.60
Pipe Insulation, 1/2", 20 ft	18.00	35.00
Pressure Relief Valve, 1/2"	6.60	10.57
Isolation Valves, 1/2"	10.32	15.78
Off-Peak Timer	25.00	15.00
2-Ton Air Conditioner	1200.00	300.00
	$3142.00	$1249.00
Total Cost	$4391.	

Conventional Solar Space and Water Heating

	Material	Labor
Solar Collectors, 9.66 m^2 (104 ft^2)	$1400.00	$ 256.60
Collector Pump, 1/12 hp	97.00	52.64
Differential Controller	88.00	40.14
Sensors (2)	18.00	32.10
Isolation Valves, 3/4"	25.20	16.62
Pressure Relief Valve, 3/4"	15.50	10.57
Vacuum Breaker	11.23	15.79
Strainer	9.40	13.21
Expansion Tank, 15 gallon	215.25	190.27
Check Valve	10.16	8.31
Storage Tank, 0.77 m^3 (206 gal) Insulated with pre-heat coil	1190.00	400.00
Copper Tubing, 3/4", 80 ft	112.80	252.00
Pipe Insulation, 3/4", 80 ft	80.00	140.00
Mounting Hardware	160.00	131.60

Conventional Solar Space and Water Heating (Cont'd)

	Material	Labor
Load Pump, 1/12 hp	$ 97.00	$ 52.64
Duct Hot Water Coil	170.00	264.26
Copper Tubing, 1/2", 20 ft	24.00	52.60
Tubing Insulation, 1/2", 20 ft	18.00	35.00
Start-up and Balancing	-	157.92
Water Heater, 0.22 m^3 (60 gal) 2-element	203.80	126.30
Electric Duct Heater, 5-kW	268.00	53.50
2-Ton Air Conditioner	1200.00	300.00
	$5413.34	$2602.07
Total Cost	$8015.	

Solar Space and Water Heating with Separate Off-Peak Storage

Cost is the same as conventional solar space and water heating system with a separate 0.929 m^3 (250 gal) off-peak storage tank for space heating and an 0.3 m^3 (80 gal) water heater replacing the 0.22 m^3 (60 gal) tank and a clock timer

	Material	Labor
Conventional solar space and water heating system minus 0.22 m^3 water heater	$5209.50	$2476.77
Water Heater, 0.3 m^3 (80 gal) 2-element	295.25	183.15
Storage Tank (Off-Peak) 0.929 m^3 (250 gal) Insulated	885.00	300.00
Immersion Heater, 15 kW	440.00	150.00
Off-Peak Timer	25.00	15.00
	$6854.75	$3124.92
Total Cost	$9980.	

Solar Air Conditioning with 27.9 m^2 (300 ft^2) Collection Area

	Installed Cost
Solar Heating System, 27.9 m^2 (300 ft^2) collectors, 2.25 m^3 (600 gal) Storage @$366.11/$m^2$($34.01/ft^2)	$10,203
2-Ton Absorption Air Conditiong Package with all Necessary Hardware	7,000
Total Cost	$17,203

Solar Air Conditioning with Off-Peak Hot Storage

	Installed Cost
Solar System, 27.9 m^2 (300 ft^2) of collectors, 2.25 m^3 (600 gal) storage @\$366.12/m^2 (\$34.01/ft^2)	\$10,203
2-Ton Absorption Air Conditioning Package	7,000
Off-Peak Storage Tank, 2.25 m^3 (600 gal), Insulated	2,600
Immersion Heater, 15 kW	590
Off-Peak Timer	40
Total Cost	\$20,433

Solar Air Conditioning System with 55.7 m^2 (600 ft^2) Collection Area

	Installed Cost
Solar Heating System with 55.7 m^2 (600 ft^2) @ \$366.15/m^2 (\$34.01/ft^2)	\$20,408
2-Ton Absorption Air Conditioning Package	7,000
Total Cost	\$27,408.

D-5. REFERENCES

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