OFF-PEAK ELECTRIC AUXILIARY HEAT FOR
SOLAR AIR-HEATING SYSTEMS

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ABSTRACT

The performance of various solar auxiliary heating system options is examined by means of computer simulation. Systems which utilize off-peak electrical energy, which is stored in a thermal reservoir for use during the on-peak period, are examined. A storage reservoir which is separate from the solar reservoir is found to be preferable. Performance is generally not found to be sensitive to the time at which off-peak energy is available. Control schemes that predict energy requirements for a forthcoming on-peak period and account for energy in solar storage are shown to be preferable. A reservoir heater that can be staged so heating can be accomplished over the full duration of the on-peak period to supply different levels of energy is found to be desirable as a means of holding down peak demand costs. The system installed in CSU Solar House I for testing is described.

INTRODUCTION

Despite the trends in the prices of energy delivered for residential use, it is generally acknowledged that economically viable solar heating systems for buildings will, for the foreseeable future, require auxiliary heating systems as a backup for extended cloudy periods. Substitutes for the conventional auxiliary systems fired by natural gas, propane, or oil are urgently needed, however, because in some instances these auxiliary sources are not available and in others their cost is becoming too high. The most likely replacement source of auxiliary energy is electricity because of its cleanliness and general availability. This backup energy source can be utilized in a number of ways including 1) direct resistance heating when demanded, 2) resistance heating of a storage reservoir at night when electrical loads are low with subsequent extraction of the energy from storage as demanded, 3) heat pump operation on demand, and 4) heat pump operation to fill an energy storage reservoir during the low electrical demand nighttime hours followed by energy removal from storage. As one progresses through this list of electrical auxiliary heating system options from first to last he finds the capital investment in the equipment becomes progressively greater and the energy costs associated with operating the system become progressively less. The energy costs decrease as one shifts from daytime to nighttime demands because utilities are generally willing to give lower nighttime rates. This encourages increased nighttime energy consumption which flattens out utility load curves, thereby facilitating more effective utilization of capital equipment. The shift to heat pumps results in a substantial

energy cost reduction because these units have a high coefficient of performance. As the coefficient of performance increases, the electrical energy required to satisfy a given heat load is reduced. Restricting the use of the heat pump to nighttime hours can result in a further reduction in the energy costs. It is well to point out, however, that heat pumps generally use resistance heaters to supplement heat pump output in cold weather. This could result in excessive electric power peaks in cold weather situations.

The study described in this report considers the use of stored energy obtained from resistance heating during the nighttime (off-peak) hours as a backup energy source to supplement the primary (solar) energy source for a home heating application. While heat pump systems also need to be considered in this application to determine if they are more cost effective than resistance heaters, the off-peak resistance system will certainly be advantageous in some applications and this study of its performance is therefore desirable. The off-peak resistive heating system is desirable because:

1. It makes use of lower cost off-peak electric power, and it therefore smoothes out the utility load making the impact of solar auxiliary positive rather than negative to the utility.
2. It is simple and can therefore be manufactured inexpensively, and
3. It can store the necessary energy at high temperatures and it therefore requires considerably less space for storage than would heat pump systems that will be available in the immediate future.

In order to demonstrate the usefulness of an off-peak electrical auxiliary heat source with a solar system the following procedure has been pursued. Simulation studies have been performed to determine

component and system designs which yield good performance. One of the preferred systems suggested by this work was then built and installed in a solar heated house for testing. This procedure is considered necessary because subsystems, such as auxiliary heating systems, cannot be simply tacked on to an existing solar system without due regard for the effects of the subsystem on overall performance. Auxiliary systems chosen for their apparent advantages based on economic and/or technical considerations must be tested just as collectors and solar storage devices must be tested. As with any other major component of a solar system, there is no substitute for operational experience in a functional system. The data obtained from such testing through a heating season is in reality the only reliable basis upon which the performance of an auxiliary subsystem, including its controls, can be evaluated. Simulation, while invaluable in relative comparisons, is not reliable as a final authority in performance evaluations on the absolute level. The testing should provide verification of the simulation and this simulation can then be extended and used to predict the effects of off-peak electrical systems in situations not encountered during the test sequence. The testing and the simulation together should therefore provide not only performance data which will be of importance to designers and users, but also data on the potential impact of such systems on electric utilities.

CHARACTERIZATION OF OFF-PEAK ELECTRIC AUXILIARY HEATING SYSTEMS

Auxiliary heat for a solar heating system can be provided by one of several off-peak electrical systems. These systems can be classified according to the storage subsystem design and the control strategy used to regulate the charging and discharging process. Each of these aspects of the system will be considered separately.

Storage Subsystem

In an effort to systematize the storage options, this subsystem is broken down into the following functional and physical options:

TABLE I. STORAGE SYSTEM OPTIONS

(i) physical structure:

organized - storage material is structured, as firebrick in a hot box.

disorganized - storage material is unstructured, as in low temperature pebble bed storage.

(ii) configuration:

separate auxiliary and solar storage

combined auxiliary and solar storage

segmentation - heat can be stored preferentially in a portion of separate or combined storage reservoirs. Segmentation might be accomplished by physical separation or by stratification like that observed in pebble beds.

(iii) heat input mechanism:

in-storage heating - heating elements are either imbedded in the storage material or the heating current passes directly through storage medium.

external heating - electrically heated heat transfer medium passes through the storage material.

(iv) temperature:

high temperature - above -100°C

low temperature - below -100°C

Each of these options results in physically different systems, but not all have to be simulated separately. For example, organized or dis-organized storage as well as temperature level makes no difference in the simulation. There are, however, certain systems which are mutually exclusive. For example, one could not have a high temperature combined storage system because flat plate solar collectors operate at low temperatures.

A thorough review of Table I suggested three system options which should be simulated and compared to determine the system which would yield the best performance and should therefore be built and tested. These system options are shown in Figure 1 in the form of energy flow diagrams. Each option is seen to include a domestic hot water load in addition to the space heating load. Valving is supplied so energy can be transferred from the collector to storage or the space heating load and so stored energy can be transmitted to the space heating load.

Figure 1a shows the combined storage system with an off-peak heater external to the storage reservoir. In this system the off-peak heater would be energized to raise the temperature of the storage reservoir during off-peak hours to such a level that the heating load could be met during the next on-peak (daytime) period. During this next day any solar energy collected would be used first to meet the heating loads and excess solar energy collected would then be added to storage. Should this collected energy be insufficient, energy would be drawn from storage

a) COMBINED STORAGE - EXTERNAL OFF-PEAK HEATER SYSTEM

b) SEPARATE STORAGE - EXTERNAL OFF-PEAK HEATER SYSTEM

c) SEPARATE STORAGE - IN-STORAGE HEATING

Figure 1. Energy Flow Schematics

and this energy would presumably be replaced the next night. During the nighttime hours when off-peak rates prevail and auxiliary heat was demanded it could be supplied directly by the off-peak heater, without passing through storage. The external heater shown in Figure 1a would be used to heat the system working fluid as it was circulated past the heater into the storage reservoir. This system could consist, for example, of a resistive heater which heats the air being circulated through a rock bed storage reservoir.

Figure 1b shows the system in which the auxiliary storage and solar storage are separate. The auxiliary storage is heated via the system working fluid from an external heater. The system of Figure 1c is essentially the same as that of Figure 1b except that the off-peak power is deposited directly in the auxiliary storage reservoir by resistance heating. In all three systems, it is assumed that auxiliary energy required during off-peak hours would be supplied directly to the space heating load via a resistance heater referred to as the night heater.

The energy storage materials that could be used in the off-peak reservoir include many that are not used in low temperature applications. The properties which one would like to see such materials possess include low cost, high density and high specific heat. A rather complete collection of properties for such materials is contained in Reference [1]. While such properties are important for the detailed design of a storage reservoir they need not be considered in the energy balance simulation which is reported herein.

The detailed design of solid storage media was undertaken during the early part of this work when it was considered improbable that a suitable off-peak storage reservoir would be available commercially. The design technique used to determine the optimum storage element size and dimensions is called the "penetration method" and is described by Arpaci [2]. Subsequently a commercially available off-peak storage unit was purchased, and the design work was therefore not converted to hardware.

Control Strategies

The strategy used to define the amount of heat that must be added to storage during an off-peak period to meet the auxiliary heating demands during the next on-peak period will influence the performance of the system. The factors which will influence the auxiliary demand are the insolation, the ambient outdoor air temperature, the energy available in solar storage, and the energy in auxiliary storage. The energy in solar and auxiliary storage can be measured directly. The average outdoor air temperature that will prevail during the forthcoming on-peak period can probably be estimated from the outdoor air temperature at the start of the off-peak period. The insolation is on the other hand highly dependent on cloud cover and cannot be readily predicted. Therefore, a practical control strategy should specify the energy to be added to auxiliary storage as a function of the energy already in solar plus auxiliary storage and the ambient air temperature.

One simple approach to the control of an off-peak electric auxiliary system is to charge the separate or combined reservoir each night with sufficient energy to meet the demand for the coming day

under the worst case outdoor temperature condition. There are two disadvantages to this approach. First, a fully charged reservoir has higher losses and hence generally yields poorer solar fractions than a partially charged one. Second, for the case of combined storage, the average temperature of the storage is higher for a fully charged system. This higher temperature results in a reduction in collector efficiency which decreases the fraction of the load carried by solar energy. It is impossible to generalize about how much of the loss from storage reservoir is eventually credited to the energy budget of the house. Yet even if everything is credited, the solar heating fraction will be adversely affected by higher reservoir temperatures. Storage losses can be reduced by a more sophisticated control strategy which predicts the amount of off-peak energy that will have to be added so the existing solar storage plus auxiliary storage will meet the design load during the on-peak period. The off-peak storage would be sized the same as in the first case, but less off-peak energy would be stored when solar storage was available.

In order to evaluate the effect of the control scheme on system performance, four different control systems were defined and used in the heating system simulations. These strategies, which are illustrated in Figure 2, are listed below.

- a) The Full Auxiliary Charge Strategy is the most conservative one.

It requires that the sufficient auxiliary energy be stored to meet the design heat load during the on-peak period. This strategy insures that adequate auxiliary heat will be available under all reasonable conditions.

Figure 2. Energy Requirement Prediction Algorithms for Four Control Strategies.

- b) The Proportional, No Solar Credit Strategy invokes the assumption that the ambient temperature at the beginning of the off-peak period is representative of the mean ambient temperature for the following day. The energy added to storage under this scheme is then proportional to the difference between the 18°C temperature, where no heat should be required, and the measured temperature. The storage is loaded to capacity only when the temperature is at or below the temperature at which full charge is desired (-10°C for the case of Figure 2). No credit is taken for energy in solar storage at the beginning of the off-peak period with this control scheme.
- c) The TPI Strategy is slightly more conservative than the Proportional No Solar Credit Strategy and is the one employed by the manufacturer of the off-peak auxiliary heating system which has been installed for test under this contract. It, like the Proportional No Solar Credit Scheme, requires that the auxiliary energy stored decrease linearly with ambient air temperature at the beginning of the off-peak period. With this scheme, however, full charge is sustained when the temperature is at or below 8°C and a minimum of half charge is maintained even at ambient temperatures above 16°C until the auxiliary system is turned off manually at the end of the heating season. With this scheme one has the option of taking credit for solar (decreasing the auxiliary by an amount equal to the solar energy stored at the start of the off-peak period) or not taking credit for it (charging auxiliary to the level indicated by the TPI curve of Figure 2 each night). Both options will be simulated.

- d) The Proportional, Solar Credit Strategy is based on experimental or simulation data. It is determined by plotting the ambient temperature at the beginning of the off-peak period against the auxiliary energy demanded during the succeeding off-peak day for the solar heated structure to which the off-peak auxiliary system is to be fitted. A typical example of such a plot obtained using data from CSU Solar House II is shown as Figure 3. Using these data a line can be drawn such that storage of the amount of energy defined by the line at the prevailing ambient temperature when the off-peak period starts will be sufficient to meet the demand a specified fraction of the time. For example, the line of Figure 3 defines the auxiliary energy that will be required to meet the demand 94% of the time. This line was actually obtained by first doing a least squares curve fit of the data above and below 0°C. The curve was then shifted vertically until the bulk of the points lay below the line. This same line is shown in Figure 2 as the Proportional, Solar Credit Strategy line. Credit is taken for stored solar energy and energy which is likely to be collected the following day with this strategy, because the curve is obtained from experimental data in which solar energy was used when it was available.

It is appropriate to note that log books suggest the data points above the line on Figure 3 were obtained in general on days when there was a heavy schedule of visitors to Solar House II and the infiltration of cold air associated with these visitors probably resulted in heat losses that would not be encountered in a private residence.

Figure 3. On-Peak Auxiliary Energy Demand as a Function of Ambient Temperature at 10 pm. (Solar House II).

The validity of the correlation between the heat loss from a structure during the on-peak period and the ambient air temperature at the beginning of the off-peak period is demonstrated by Figure 4. These data were collected at Colorado State University during the winter of 1977-78 and they assume the on-peak period is from 6 am to 10 pm and the off-peak period is from 10 pm to 6 am. The least squares curve fit of the data is shown as the solid line. It is noted that on only 10% of the days considered in Figure 4 was the average temperature significantly below the ambient temperature at 10 pm. If solar energy had not been available on these days and the off-peak auxiliary storage had been charged in accordance with the No Solar Credit Strategy, the stored auxiliary energy would have been insufficient to meet the demand. Solar energy was, however, available during the next on-peak period sufficiently often that the auxiliary energy would not have been available on only 4% of the days.

Figure 4. Ambient Temperature at the Beginning of the Off-Peak Period vs. Average Ambient Temperature During the Following on-Peak Period.

SIMULATION OF OFF-PEAK AUXILIARY SYSTEMS

Two separate simulation techniques were used to evaluate the system options discussed in the previous section. The first simply involved taking the actual auxiliary heat load data for a given house and applying different control strategies to determine how well each one would have performed had that strategy been applied. The hourly auxiliary energy demand for CSU Solar House II [3] for the period November 11, 1976, to March 10, 1977, were used as input to this simulation model. Results obtained pertain then to a system employing the stratified storage of Solar House II and a separate auxiliary storage reservoir maintained in accordance with the control strategy specified in the simulation.

The second simulation technique involved modelling each of the different off-peak storage concepts and control strategies using the program TRNSYS [4]. TRNSYS is a simulation program with modularized solar components which the user can inter-connect into the desired system. If additional routines are desired (such as auxiliary storage and special controller) these units can be programmed by the user and incorporated into TRNSYS. The program increments through the selected weather period in small (typically 15 minutes) time steps, and calculates the steady state flow rates, temperatures and energy flows. This model was more expensive to operate than the first one, but it allowed performance comparisons for any system.

TRNSYS Simulation Description

For this particular study, a standard weather tape for Boulder, Colorado, was used as input to TRNSYS. Hourly values for the ambient temperature and solar insolation on the horizontal surface are read,

Linear interpolation was assumed at intermediate points. The period selected for study was approximately the first 35 days of the standard year.

The wall and ceiling insulation values, domestic hot water heat load and collector and solar storage reservoir characteristics of CSU Solar House II (3) were used as input to the simulation. The characteristics of this house were used in these simulation studies because it was considered to be the house in which the system tests were most likely to be conducted. The hourly heat loss rate from the heated space was calculated using a simple conduction model recommended by the American Society of Heating, Refrigeration and Air Conditioning Engineers [5]. The domestic hot water load turned out to be about 300 liters/day at water inlet and outlet temperatures of 6.1°C and 60°C respectively. CSU Solar House II is equipped with an air-cooled solar collector and a stratified storage box utilizing gravel as the storage medium. Collector control is achieved in this system by turning on the collector blower to circulate solar heated air through the house or storage when the collector outlet temperature is 10°C greater than the input; it remains on until this temperature differential is less than 5°C . The domestic hot water controller also circulates domestic water through its heat exchanger when the water side temperature rise would be 10°C and it turns off when this differential drops to 5°C .

The Solar House II thermostat is a two stage device; when the room temperature drops below 21°C , energy is extracted from the solar heating system. If the room temperature drops below 20°C , heat is drawn from auxiliary storage, until the temperature again exceeds 21°C . This thermostat strategy was used in all simulations but was modified for

the case of the combined storage mode where only one storage reservoir is available. In this case, a single stage thermostat set at 21°C was used in the model. In all simulations however, the direct use of electrical energy was not allowed during the daytime hours when off-peak electrical rates were not in effect.

Each of the heat storage reservoirs used in the simulations was sized such that it could supply the energy needed to heat the building over the full 16 hour on-peak period if the outside air temperature was maintained at the design value of -23°C throughout this period. Since this design condition occurs infrequently, the storage volumes are conservatively large. For the systems employing separate auxiliary storage (Figures 1b and 1c) the size of a rock bin containing 3/4" diameter rock sufficient to meet this storage condition would be a cube 2.7m on a side. Solar storage would be the same size in these two cases. For the combined solar/auxiliary storage case (Figure 1a) the volume of this single storage reservoir was set equal to that of the solar plus auxiliary for the other two cases.

These storage volumes are based on a maximum storage temperature of 60°C which is the maximum temperature that can be discharged into an inhabited space without introducing a danger of burning the occupants. Higher auxiliary storage temperatures and correspondingly smaller auxiliary storage volumes can be realized in the in-storage heated systems and the danger of burns can be made acceptably low by diluting the air from storage with room air. Changes in the storage temperature and volume of this sort do not change the results of the simulation.

The heat loss from any of these reservoirs was determined by the insulation U-factor which was specified as $2.5 \text{ KJ/hr}^\circ\text{C}_m^2$. This is the

U-factor for the insulation of the rock storage reservoir installed presently in Solar House II. Heat removal from the storage reservoir to the heat load was modelled by specifying an air flow rate of 1975 kg/hr through the storage reservoir. The externally heated auxiliary reservoirs (Figures 1a and 1b) were modelled as stratified units and heated air was assumed circulated through them at a flow rate of 3900 kg/hr during the charging process. The in-storage heated reservoir (Figure 1c) was modeled as unstratified and of course no flow rate was specified through it during the charging process.

The maximum auxiliary charging rate is defined as the ratio of the maximum energy that can be transferred to storage divided by the duration of the off-peak period (typically 8 hours). It is obvious that the demand on the electric utility can be reduced by increasing the duration of the off-peak period. It can also be reduced by segmenting the heaters used to supply energy to the auxiliary storage so partial charges can be supplied to the storage by operating a fraction of the heaters over the full off-peak period. The effect of changing the number of heaters capable of producing the maximum auxiliary charging rate was varied in this study to determine the effect of heater segmentation on the level of energy demand (peak power demanded during a month). The heat load during the nighttime (off-peak) hours was met by a night heater and the effect of segmenting this heater was also examined. During the off-peak hours then one would expect the charging heater to be on continuously and the night heater to be on periodically as the thermostat called for auxiliary heat. The effect of using the night heater to swing over and heat storage when the thermostat was not

calling for heat was also considered. Operating in this way it was possible to hold the demand constant during each off-peak period at a value which approached the mean power demand observed when the night heater was cycled.

Figure 5 shows frequency of auxiliary energy demand as a function of time of day for the house which has been modelled (Solar House II) with the demand level indicated by the code given in the box. The figure shows for example that on 30% of the days some auxiliary energy was demanded between midnight at 1 am and that about 8% of these demands were in the range 0.1 to 10 MJ/hr. From this figure one can see that energy is demanded between midnight and 9:00 am most frequently. One also observes that the bulk of the demands are 30MJ/hr or less. The highest demand level observed was 70 MJ/hr and it and other high demand levels occurred late in the afternoon presumably because of visitor induced infiltration loads.

The on-peak period defined for this study was 6 am to 10 pm and since heat is removed from auxiliary storage to meet these demands the total demand over this period is more useful than the hourly demands. This total demand divided by the off-peak period (8 hrs. in this case) determines the required power level of the storage heaters. The peak nighttime auxiliary heat demand determines on the other hand the night heater power level.

The maximum total on-peak demand for Solar House II was about 400 MJ so 50 MJ/hr charging capability over an 8 hr. off-peak period was selected as sufficient to meet the worst case storage heating demand in the simulation. The maximum off-peak demand was observed to be less than 60 MJ/hr so the night heater was sized at 60 MJ/hr for the simulation runs.

Figure 5. Auxiliary Demand vs. Time of Day CSU Solar House II over Typical 76-Day Winter Period.

SIMULATION RESULTS

The effects of control scheme and the degree of segmentation used in the heaters were examined initially by considering the auxiliary energy demanded hour by hour for Solar House II during a typical winter period. The results of these simulations are presented as Table II. For each control strategy, three different heating element staging configurations (i.e. one, two or four power levels) were examined. For each of these the following results are presented in Table IV: a) the total electrical energy that had to be consumed during the off-peak period to meet the on and off-peak heating loads, b) the maximum rate of electrical energy demand during the simulation period, and c) the net on-peak energy deficit. The net on-peak energy deficit reveals the amount of additional energy that would have had to be supplied during on-peak hours to sustain the house comfort level under the given strategy, and it is a measure of the off-peak system's inability to supply the auxiliary energy needs completely.

The results show that element staging affects the total energy consumed only slightly, but has a more pronounced effect in reducing electrical demand. It is observed, however, that the total energy requirement can be significantly reduced by predicting the actual auxiliary load requirements more closely. The penalty for the reduced energy consumption is more frequent excursions from the desired control temperature as indicated by the increase in net on-peak energy deficit as the control strategy shifts from the full charge to the no solar credit to the solar credit strategies.

TABLE II Tabulation of off-peak auxiliary system performance - Solar House II data for period November 11, 1976, to March 10, 1977.

Strategy	# of Stages*	OFF-PEAK		Net On-Peak Energy Deficit(MJ)
		Energy (MJ)	Demand (MJ/hr)	
Full Charge	1	21164	110	0
	2	21018	110	0
	4	20752	95	9
Proportional No Solar Credit	1	17625	110	274
	2	17495	105	270
	4	17272	95	289
Proportional Solar Credit	1	15017	110	797
	2	14970	80	790
	4	14802	82.5	820

* Heat Segmentation Specification:

- 1 stage - one night heater element: 60 MJ/hr
one storage heater element: 50 MJ/hr
- 2 stage - two night heater elements: 30 MJ/hr each
two storage heater elements: 25 MJ/hr each
- 4 stage - four night heater elements: 15 MJ/hr each
four storage heater elements: 12.5 MJ/hr each

It should be pointed out here that the auxiliary storage reservoirs modelled in this work were poorly insulated. This resulted in significant energy leakage. If this leakage occurred during a time when heat was being demanded, it was used to satisfy the heat load. If it occurred when heat was not being demanded, it was presumed lost from the house by the action of a resident who might open a window.

On the basis of the results obtained using the Solar House II auxiliary load data, the full system model was simulated using the program TRNSYS. The total heater power (charging plus night heater) was increased to 150 MJ/hr for these runs in an effort to reduce the on-peak deficit encountered in the earlier work. The heaters were segmented into five 30 MJ/hr elements. One of the heater sets, referred to as the "swing" unit, was used to simulate air heating to satisfy the nighttime heating load, when this heat was demanded. During the period when there was no nighttime demand, it was either switched over to heat auxiliary storage or if its continued use would result in over-charging the storage, it was switched off. The other three units were switched over to heat storage along with the periodically available "swing" heater as necessary to meet the predicted auxiliary heat load. Operation using the "swing" heater in this way helped to reduce power peaks and hold down demand charges. When nighttime ambient temperatures dropped below 0°C and the single "swing" heater could not meet the nighttime heating load alone, another one of the heaters would be operated in the swing mode to achieve the desired nighttime heating power. The control strategy used in all of these simulations was the full charge one. This was done because it was believed that the reduction in energy demand which would be realized with

the more complex control scheme would be insufficient to justify the occasional discomfort which would accompany it. This conclusion was reached by considering the data of Table II.

The simulation program outputs instantaneous values of temperature and flow rates periodically throughout each day, plus daily total energy usages at various points in the system. The comparative results obtained for the models of the three systems of Figure 1 are presented in Table III. The integrated energy values are given in Megajoules and are reported for the complete 35 day simulation period. The total energy demanded for the period Q_T consists of the space heating load (Q_{sh}) and the domestic hot water heating load. The solar energy delivered from the collectors (Q_u) either goes directly toward meeting this load (Q_{dir}) or it passes through storage (Q_{sto}). In the case of the combined solar/auxiliary storage system this stored energy consists of both auxiliary and solar-derived energies since they are stored together. The fraction of the load that cannot be met using solar energy is met by auxiliary energy (Q_{aux}) supplied either directly (Q_{da}) or through auxiliary storage (Q_{sa}) or it comes from storage losses (Q_{loss}) which are assumed to pass to the house continuously thereby reducing the heating load. These losses consist of losses from either storage reservoir or from the hot water heater. The fraction of the load carried by solar (f) is given by $f = Q_u/Q_T$. An energy balance over the duration of the simulation showed the net energy transfer agreed with the change in the energy stored to within about 1%. This indicates the simulation closure is sufficiently close to yield valid results.

The data in the last five lines at the bottom of Table III gives the frequency of the maximum daily electrical demand for the off-peak

TABLE III. TRNSYS Simulation Results (Energies over 35-Day Period-MJ)

CASE	A Combined Storage External Heater	B Separate Storage External Heater	C Separate Storage Instorage Heater	D Combined Storage External Heater 1/3 Reduction in Storage	E Separate Storage Instorage Heater 12 pm-8 am Off-Peak
Total Load, Q_T	24400	24200	24200	24600	24200
Space Heating Load, Q_{sh}	22000	21900	21900	22200	21900
Collected Solar, Q_u	15400	16500	16500	13900	16500
Directly used Solar, Q_{dir}	8520	5050	5090	7980	4990
Energy through Solar or Combined Storage, Q_{sto}	12600	8870	8890	12500	8900
Auxiliary Energy Q_{aux}	9780	8100	8790	11700	9010
Directly Used Aux. Q_{da}	-0-	1850	2680	-0-	3230
Aux. through Storage Q_{sa}	-0-	3040	2950	-0-	2340
Storage Losses to house Q_{loss}	1390	2720	2730	2350	2830
Fraction of load carried by Solar - f	63%	68%	68%	57%	68%
Frequency of Daily Demand Levels					
0 - 30 MJ/hr	18	25	24	10	24
30.1 - 60 MJ/hr	8	7	7	15	7
60.1 - 90 MJ/hr	6	1	2	8	2
90.1 - 120 MJ/hr	3	2	2	2	2
120.1 - 150 MJ/hr	0	0	0	1	0

systems in various ranges. For example, the externally heated separate storage system required a maximum of only one heating element (30 MJ/hr) on 25 simulated days; two 30 MJ/hr elements were required on 7 days; three of the elements were required on one day; and all four elements were required on two days. The cases simulated included the three systems described in Figure 1 (A, B and C), Case D wherein the simulation of Case A was repeated using a 33% smaller combined storage volume, and Case E where Case C was repeated using a 12 pm to 8 am off-peak period rather than the 10 pm to 6 am period used in the other cases.

There are two viewpoints that must be considered in selecting an off-peak electric thermal storage system. From the users viewpoint, the total purchased energy should be minimized. In other words, the fraction of the load supplied by solar must be maximized to obtain the greatest return on investment. However, the utility must consider not only the total energy requirement, but also the rate of energy consumption (demand). Therefore, the system preferred by both user and supplier would provide the minimum energy at the lowest demand rate. With these criteria in mind, consider the results for the various runs as presented in Table III. A comparison of the data in the table suggests that the two separate auxiliary storage systems (Cases B and C) exhibit essentially identical performance. This is as one would expect, considering the nature of TRNSYS is to balance energies. The solar fraction for the combined system is significantly lower than for the separate systems. This is because the useful energy delivered by solar is about 5% lower for the combined storage system than it is for the separate storage one. This probably occurs because the higher average

storage temperature in the combined storage results in a higher supply temperature to the collectors, and thereby causes them to operate less efficiently. This was substantiated in the simulation by observing that the energy delivered to the domestic hot water preheater was substantially higher in the combined storage cases. The higher energy delivery in the combined storage cases implies a higher air temperature in the heat exchanger. Since the insolation rate and ambient temperature for all runs are identical, higher collector outlet temperatures imply higher inlet temperatures. It is important to recall here that the combined storage reservoir was modelled as a stratified rock box, so the higher collector inlet temperatures are not a consequence of mixing in storage. They occur instead because of the higher average temperature in storage accompanied occasionally by thermal breakthrough.

The second simulation assuming combined storage is shown in column D. In this case, the storage volume was reduced by 33% to a volume that is approximately twice the existing capacity of Solar House II. This resulted in a noticeable decrease in the solar fraction, and a corresponding increase in auxiliary requirements because of the increase in storage temperature necessitated by this reduction in storage size. These results indicate that separate auxiliary storage is desirable, based on lower auxiliary energy requirements, and slightly reduced frequency of high levels of demand on the utility. These results are in agreement with similar studies performed at the University of Wisconsin [6].

Another parameter of interest to both the consumer and the utility is performance sensitivity to the hours of off-peak operation. To

examine the effect of changing this parameter, the simulation of the Separate Storage-Instorage Heater system was repeated with the off-peak period changed from 10 pm - 6 am to midnight - 8 am daily. The results are shown in Column E. No significant change in long-term performance was observed, but the operation of the system was modified, in that a larger fraction of the auxiliary requirements was satisfied directly by night auxiliary. As a result, a proportionately smaller fraction passed through storage to the load. This occurred because about 25% of the total auxiliary energy needs occur between the hours of 6 am and 8 am. That this is the case can be seen in Figure 5 which shows the auxiliary demand by hour of the day for Solar House II. Under this circumstance, the solar storage system is frequently depleted by 6 am, and insolation rate is not sufficient to justify direct solar heating until after 8 am. Although the daily operation of the auxiliary system changes as a result of this change in the off-peak period, it is interesting to note long-term performance of the system is not altered significantly.

Effect of Auxiliary Storage Insulation

Thermal losses from auxiliary storage to the house were significant in each system simulated. In fact, about 40% of the thermal energy sent to auxiliary storage was lost to the heated space. This study assumed these losses generally reduced the heating load for the house but the detailed effects of these losses was not known. They could obviously be reduced by increasing insulation on the auxiliary storage reservoir--the above runs assumed the same auxiliary storage insulation values ($U = 2.5 \text{ KJ/hr}^\circ\text{C}_m^2$) used in the Solar House II storage reservoir.

The system model utilizing separate storage with externally heated auxiliary was rerun with several different auxiliary reservoir insulation values. The results of these simulations are compared to Case B of Table III in Table IV. These data show that losses do not hurt overall system performance significantly over a reasonably large range of insulation value. As long as the heating load is greater than the losses, the losses simply shift the delivery schedule of auxiliary energy, and increase the amount of auxiliary energy that must be purchased only slightly.

Effect of Control Strategy

The preliminary investigation of which control strategy would be best suited to each of the system options had been based on a simple simulation which looked at the auxiliary demand from Solar House II. Another TRNSYS simulation was run to determine the effect the control scheme would have on the performance of the separate storage systems which appeared to be most promising. In this simulation case C (Separate Storage - Instorage Heater) was rerun using the least conservative control strategy (the Proportional, Solar Credit Strategy). This facilitated the comparison of the full charge and proportional solar credit strategies which are given in Table V. This Table shows that in the case of the proportional solar credit strategy the solar energy collected is up slightly, probably reflecting the slightly lower average solar storage temperature. The auxiliary storage losses have been reduced dramatically, since the auxiliary storage tended to run only a few degrees above the zero energy stored level. The purchased energy for this 35 day period Q_{aux} has dropped from

TABLE IV Simulation Results Effect of Insulation of Auxiliary Storage (Energies in MJ)

CASE	B Standard Insulation 2.5 KJ/hrm ² °C	F Ten Times Insulation Level 0.25 KJ/hrm ² °C	G One Half Insulation Level 5 KJ/hrm ² °C	H One Fourth Insulation Level 10 KJ/hrm ² °C
Total Load, Q_T	24200	24200	24300	24500
Space Heating Load, Q_{sh}	21900	21800	22000	22100
Collected Solar, Q_u	16500	16600	16200	15600
Directly Used Solar, Q_{dir}	5050	5460	4460	3500
Energy through Solar Storage, Q_{sto}	8870	8770	9040	8940
Auxiliary Energy Q_{aux}	8100	7490	8580	9840
Directly used Aux. Q_{da}	1850	2130	1410	1040
Aux. through Storage Q_{sa}	3040	3900	2360	1250
Storage losses to house, Q_{loss}	2720	719	4660	7880
Fraction of load carried by solar - f	68%	69%	67%	64%

Frequency of
daily demand levels

0 - 30 MJ/hr	25	24	22	21
30.1 - 60 MJ/hr	7	8	9	8
60.1 - 90 MJ/hr	1	2	3	3
90.1 - 120 MJ/hr	2	1	1	2
120.1 - 150 MJ/hr	0	0	0	1

TABLE V Comparison of Least and Most Conservative Control Strategies -
Separate Storage Instorage Heating (Energies in MJ)

CASE	C Full Auxiliary Charge Strategy	I Proportional, Solar Credit Strategy
Total Load, Q_T	24200	23400
Space Heating Load, Q_{sh}	21900	21000
Collected Solar, Q_u	16500	16800
Directly used Solar, Q_{dir}	5090	6680
Energy through Solar Storage, Q_{sto}	8890	7910
Auxiliary Energy Q_{aux}	8790	6350
Directly used Aux. Q_{da}	2680	4880
Aux. through Storage Q_{sa}	2950	1370
Storage Losses to house, Q_{loss}	2730	522
Fraction of load carried by solar - f	68%	72%

Frequency of
Daily demand levels

0 - 30 MJ/hr	24	34
30.1 - 60 MJ/hr	7	1
60.1 - 90 MJ/hr	2	0
90.1 - 120 MJ/hr	2	0
120.1 - 150 MJ/hr	0	0

8790 MJ to 6350 MJ and the solar fraction increased from 68% to 72%. This result suggests that the control strategy has a significant influence on long term system performance.

On only one day did a base load heater have to be used to charge the auxiliary storage for the proportional solar credit case, although the off-peak power was required practically every night for direct heating using the night heater element. These results suggest that the use of the proportional solar credit strategy could result in substantial cost savings for a home owner over the full charge strategy system. The cost savings occur not only in terms of reduced energy cost, but more significantly in demand costs and to a lesser extent because of a lower capital investment in the auxiliary storage reservoir. The reduction in the demand levels is also very significant from the point of view of the utilities. The fact that demand levels are reduced means that the impact of solar systems on days of low temperature and insufficient insolation will be reduced and it also means the capital investment in distribution equipment for homes can be reduced.

The penalty for this improved thermal performance observed with the proportional solar credit strategy is an occasional lowering of the temperatures in the controlled space. The extent of the discomfort caused by this control scheme is indicated in Table VI. With the full auxiliary charge strategy the space temperature remained above 19°C. Table VI gives the frequency of room temperature occurrences less than 19°C occurring over the 35-day period simulated. Temperatures were below 19°C only about 6% of the total simulation time (840 hrs.). The

lowest apparent temperature was 16.52°C, which is only a few degrees below the government-suggested thermostat setting of 18.3°C.

TABLE VI
Frequency of Low Temperatures
for the Proportional Solar Credit Strategy
over 35-Day Heating Period

<u>Temperature Range</u>	<u>Time in Temp. Range</u>	<u>% of total time</u>
18.5 - 18.99°C	20 hours	2.4
18.0 - 18.49	12	1.4
17.5 - 17.99	8	.95
17.0 - 17.49	4	.48
16.5 - 16.99	6	.72

The TPI control strategies both with and without taking credit for the energy stored in the solar storage reservoir were also analyzed using the program TRNSYS. These two strategies represented the ones which could be implemented readily in the actual hardware to be used in the experimental studies. The results of these simulations are compared to the full auxiliary charge strategy (Case C) in Table VII. The system representation for each of these cases is the Separate Storage-In-Storage Heating one (Figure 1c) which is representative of the TPI hardware.

In all of the cases shown in Table VII the performance is similar. The losses from auxiliary storage were observed to be significantly higher with the TPI unit which stores its energy at very high temperatures, but this did not affect the results significantly because adequate

TABLE VII. Effect of TPI Control Strategy on System Performance
(Energies in MJ/hr)

CASE	C Full Charge Auxiliary Strategy	J TPI Strategy No Solar Credit	K TPI Strategy with Solar Credit
Total Load, Q_T	24200	24200	24200
Space Heat Load Q_{sh}	21900	21800	21800
Collected Solar Q_u	16500	16500	16500
Directly used Solar, Q_{dir}	5090	5080	5020
Energy through Solar Storage Q_{sto}	8890	8860	8960
Auxiliary Energy Q_{aux}	8790	8366	8132
Directly used Aux. Q_{da}	2680	2490	2640
Aux. through Storage Q_{sa}	2950	2840	2900
Storage losses to house Q_{loss}	2730	3110	2810
Fraction of load carried by solar - f	68%	68%	68%
Frequency of Daily demand Levels			
0 - 30 MJ/hr	24	29	33
30.1 - 60 MJ/hr	7	4	1
60.1 - 90 MJ/hr	2	1	1
90.1 - 120 MJ/hr	2	1	0
120.1 - 150 MJ/hr	0	0	0

insulation is provided in the unit. The demand levels are however observed to be considerably less for the TPI unit particularly when credit is allowed for solar energy stored. This would result in lower customer demand charges and less severe demand levels on the utility companies.

In addition to the daily maximum demand rate, it is sometimes useful for a utility to know the daily demand profile. This will help the utility to better anticipate the impact of solar installations. The demand profiles will be presented for three cases; 1) the measured profile for C.S.U. Solar House II, 2) the separate storage, externally heated case with the full auxiliary charge capacity (Case C - Table III), and 3) the TPI system without Solar Credit (Case K - Table VII). The demand profile for the base case (the measured auxiliary hourly demand in Solar House II for the period November 11, 1976, to March 10, 1977), was shown previously in Figure 5. Note that this system does not include any off-peak equipment nor auxiliary storage. For each hour of the day the frequency of the delivered auxiliary demand in 10 MJ/hr bands is given. For example, between midnight and 1:00 am, during the 76 days considered, eight percent required less than 10 MJ/hr during this hour; twelve percent required 10 to 20 MJ/hr of auxiliary; nine percent needed 20 to 30 MJ/hr; and one percent required over 30 MJ/hr during that hour. The highest and most frequent energy demand occurred during the early morning hours. The demand frequency dropped drastically after 9:00 am, and remained low through the afternoon and early evening. The frequency and demand increased through the night to the early morning highs. Note that these data are for typical weather

conditions, but are not identical with the following two cases. Therefore, direct comparisons should be avoided, and only general trends considered.

The second case is for the separate off-peak auxiliary storage system with an in-storage heater modelled using TRNSYS and reported as Case C of Table III. This case is considered representative of the several "full charge" systems studied and is shown in Figure 6. There is, of course, no electrical energy supplied between 6 am and 10 pm. However, there is a significant change in demand at 10 pm, with demand and frequency tapering off toward morning.

The third case is for the TPI unit with solar credit and it is given in Figure 7. This represents the configuration installed for testing. Again, there is a large change in demand at 10 pm, however the need for some electrical energy tends to occur essentially every day while high demand levels are less frequent. It is appropriate to point out that the high demand levels observed in Figure 7 occur because the night heater comes on while the unit is being charged and this produces high power peaks. If this unit were operated in a swing heater mode where storage heaters were cycled off as the night heater came on so the power level was held constant these peaks could be reduced substantially (Fig.6). It is also important to note that the power meters used by utilities frequently determine peak demand by integrating the power over a fifteen minute time interval. Since the night heater is generally on for only a fraction of this 15 minute interval, the meter could read a peak power considerably less than the instantaneous night heater power which are part of Figure 7.

Figure 6. Demand Profile - Case C

Figure 7. Demand Profile - Case K
TPI Unit as Built (with Solar Credit).

Figure 7 suggests that the use of a more accurate predictor of the heat load during a forthcoming on-peak period results in not only lower demand levels but also more constant energy input levels than does the Full charge strategy (Case C - Fig. 5). This is shown by the fact that some energy is demanded between 70% and 80% of the off-peak hours for the TPI strategy case of Figure 7 compared to 30% to 50% for the full charge strategy in a situation where the TPI strategy required less total energy. This should result in more evenly distributed off-peak loads for the utilities.

CONCLUSIONS

1. Separate auxiliary storage systems provide superior performance to combined storage systems (typically a 5% increase in solar fraction).
2. Performance is not sensitive to the time selected for the off-peak period, although duration of the off-peak period will effect the demand levels.
3. Performance is relatively insensitive to the rate of auxiliary storage losses if the losses are to the heated space.
4. The hourly demand profile can be made significantly more uniform and demand levels can be reduced by using strategies that predict the energy storage requirements with reasonable accuracy. The long-term solar performance is not affected significantly by these control strategy changes.
5. The rate of energy demand can be reduced by providing sequential stages of demand.

EXPERIMENTAL APPARATUS

The off-peak furnace to be tested as an auxiliary heat source for a solar heated house is the 200kwhr storage capacity unit manufactured by TPI Corporation of Johnson City, Tennessee [7]. This unit is being installed in CSU Solar House I [8] and will be tested over a heating season in a system consisting of evacuated tube collectors manufactured by Philips GmbH Forshungs laboratoriumAachen of Germany and an 1100 gallon water-filled, solar storage reservoir. The off-peak auxiliary unit will fit into the system in the manner suggested by Figure 8. Ambient return air will first be drawn through a heat exchanger where hot water from the Solar heated storage tank will be used to raise its temperature. If the heat added is insufficient to maintain the house temperature additional heat will be added before the air is distributed to the house. The additional heat, which will be added if necessary, will come from the night heater if it is called for during off-peak hours or from the off-peak storage unit if it is demanded during on-peak hours.

Auxiliary Storage Unit

The storage core of the TPI unit contains about 1360 kg of core blocks capable of storing about 200 kwhr of thermal energy at about 760°C. Maximum temperature for this test will, however, be limited to about 580°C where the storage capacity is about 160 kwhr. The overall size of this core section is 1.3m high, 1.2m wide and 0.7m deep. Passages exist in the core through which air can pass and be heated. After this air leaves the core, it is tempered with by-pass air to obtain the desired outlet temperature for distribution through the house. The core is insulated by a 2.5cm thick layer of Vicuclad next to the core blocks,

Figure 8. As Built System Schematic

followed by 2.5cm of microtherm and finally 5 to 10cm of Rocksil. This insulation is sufficient to limit the heat loss rate from the unit to about 2kw when the core temperature is 580°C.

Eleven electric resistance heaters are sandwiched between the twelve layers of blocks used in the unit. The elements are made of heavy gauge nichrome wire formed into open spiral coils. With the 208V operating voltage applied across a heater element it will pass about 9 amperes of current and dissipate about 1900 watts.

Three types of thermally responsive devices are used to monitor, control and safeguard the electric thermal storage process. These devices sense core temperature and include a thermocouple designed to limit charging to 580°C, automatic reset limits designed to terminate the heater current at 790°C and a manual reset limit designed to terminate the heater current at 850°C.

Night Heater Section

This section is 1m high, 0.5m wide and 0.5m deep. It is located downstream of the storage unit and it consists of a 1/3 hp motor-centrifugal fan and three resistance type heating elements which operate at 3.8kw and are used for nighttime heating of the house. These elements may also be energized manually to supply on-peak heat to the house on demand. It is not anticipated that this feature will be used during the test.

Controls

The required storage charging rate is determined before each off-peak period. To do this, the outdoor ambient temperature is measured at the beginning of the off-peak period and this temperature is used in

a logic circuit to determine the amount of heat which is to be stored for auxiliary heating during the on-peak period. Some updating is effected to turn on or off additional heaters if the outside temperature drops or rises substantially during the charging period. The amount of energy required in storage at the end of the off-peak period is defined by the TPI Strategy curve of Figure 2. Millivolt signals proportional to the temperature of the off-peak stored energy and the energy stored in the solar heated reservoir are then added to obtain a signal proportional to the energy stored at the start of the off-peak period. The difference between the energy stored and that required is divided by the off-peak time interval of 8 hours which is built into the controller logic. Based on this computed charging rate, the required number of core heaters are energized. The nominal power levels which can be used for core heating are:

- 1st level - 7.6 kw
- 2nd level - 13.3 kw
- 3rd level - 17.1 kw
- 4th level - 20.9 kw

Heat transfer to the house from solar and auxiliary storage are controlled by the house thermostat. This thermostat is a two-stage device set at 21°C for 1st stage heating and 20°C for 2nd stage. When 1st stage heating is called for, the fan and house heating pump (Fig. 8) are energized. If the heat supplied from the solar reservoir is sufficient this fan and pump will cycle off when the house temperature reaches 22°C. If the heat supply rate is insufficient, energy is drawn from the off-peak furnace. If this demand for auxiliary energy occurs during the off-peak period, the night heaters are energized to

boost the temperature of the air being circulated through the Solar heat exchanger. If the demand occurs during on peak hours, a set of dampers is energized within the off-peak furnace. These dampers deflect some of the solar heated air through the auxiliary storage core to achieve the necessary temperature boost. This hot air is then mixed with the solar heated air and the temperature of the mixture is sensed. This temperature is fed back to the damper control system and the dampers are adjusted to maintain the desired supply air temperature to the house.

Should the temperature of the solar storage drop to 24°C the pump circulating water from solar storage is shut off and the entire heating load is supplied from the off-peak auxiliary unit.

Present Status

The off-peak auxiliary storage unit has been installed and all electrical circuits and controls have been checked out. The unit is instrumented in such a way the following data can be collected:

- Daily on-peak maximum power to unit
- Daily on-peak energy supplied to unit
- Daily off-peak maximum power to unit
- Daily off-peak energy supplied to unit
- Continuous energy in auxiliary storage
- Continuous power to house air from solar storage
- Continuous power to house air from off-peak storage
- Continuous power to house air from night heater

The points at which Temperatures T , daily peak power P and daily energy E will be measured are indicated on Figure 8.

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