SOLAR PHOTOVOLTAIC/THERMAL RESIDENTIAL SYSTEMS

Miles C. Russell

DISCLAIMER

This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

28 December 1979

Massachusetts Institute of Technology
Lincoln Laboratory
Lexington, Massachusetts 02173

Prepared for the
U.S. DEPARTMENT OF ENERGY
UNDER CONTRACT NO. EY-77-S-02-4577

leg

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

This report presents the results of a conceptual design study using computer simulations to determine the physical and economic performance of combined photovoltaic/thermal collector heat-pump solar systems for a single-family residence. Economic analyses are based upon projected costs for a 1986 system installation. The results show that PV/T collector systems can be economically competitive for a cold climate residence, that systems employing on-site electrical storage batteries are not economically competitive with utility-interactive systems, and that an ambient-air-source heat-pump system has a lower life-cycle cost than a solar-source heat-pump system.

ABSTRACT

This report presents the results of a conceptual design study using computer simulations to determine the physical and economic performance of combined photovoltaic/thermal collector heat-pump solar systems for a single-family residence. Economic analyses are based upon projected costs for a 1986 system installation. The results show that PV/T collector systems can be economically competitive for a cold climate residence, that systems employing on-site electrical storage batteries are not economically competitive with utility-interactive systems, and that an ambient-air-source heat-pump system has a lower life-cycle cost than a solar-source heat-pump system.

TABLE OF CONTENTS

<u>Section</u>		<u>Page</u>
	Abstract	iii
	List of Figures	vii
	List of Tables	viii
1.0	INTRODUCTION	1
	1.1 Objectives	1
	1.2 Summary and Conclusions	1
2.0	ANALYSIS METHODOLOGY	3
	2.1 Meterological and Heating/Cooling Data	3
	2.2 Residential Loads	6
	2.3 Residential Energy System Concepts	7
	2.3.1 Series or Solar-Source Heat-Pump Thermal Subsystem	9
	2.3.2 Parallel or Ambient-Air-Source Heat-Pump Thermal Subsystem	11
	2.3.3 Utility-Interactive Inverter Electrical Subsystem	12
	2.3.4 DC Electrical Subsystem with Storage	12
	2.4 Component Models	12
	2.4.1 Heat Pumps	14
	2.4.2 Photovoltaic/Thermal Collector	16
	2.4.3 Electrical Subsystem Components	18
	2.4.4 Thermal Subsystem Components	18
	2.5 Economic Analysis	18
3.0	RESULTS	25
	3.1 New York Residence System Performance Results	25
	3.2 New York Residence System Economic Forecasts	28
	3.3 Fort Worth System Performance Results	32
	3.4 Fort Worth Residence System Economic Forecasts	33
4.0	CONCLUSIONS	35

TABLE OF CONTENTS (CONTINUED)

<u>Section</u>		<u>Page</u>
5.0	HARDWARE CONSIDERATIONS	36
5.1	Constraints on System Complexity	36
5.2	Hardware Availability and Cost	39
5.3	Carrier Corporation's "Solaround" System	39
5.3.1	Variable-Speed Compressor	39
5.3.2	Collector Fluid	40
5.3.3	Tri-X Coil	40
5.3.4	Desuperheating of the Compressor's Discharge Line	42
5.3.5	Resistance Heating	42
5.4	Modified Solaround System Inventory	43
5.5	Combined Photovoltaic/Thermal Collectors	45
	REFERENCES	47

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Meteorological and Residential Space Conditioning Load Quantities on Magnetic Tape	5
2	Residential Heating and Cooling Demand	6
3	Monthly Supply Water Temperature	8
4	Combined Photovoltaic/Thermal Collector Performance Characteristics	16
5	System Economic Assumptions	19
6	Component Price Assumptions	19
7	Energy Performance of a New York Residence Utilizing Separate Photovoltaic and Thermal Collectors	28
8	Levelized Annual Cost of a New York Residence Utilizing Separate Photovoltaic and Thermal Collectors	31
9	Energy Performance of a Fort Worth Residence Utilizing Separate Photovoltaic and Thermal Collectors	33
10	Levelized Annual Cost of a Fort Worth Residence Utilizing Separate Photovoltaic and Thermal Collectors	34
11	Carrier Corporation Components Included in PV/T Prototype System	44
12	Remaining Components Included in PV/T Prototype System	44

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Procedure flowchart	4
2	Domestic hot water demand profile	7
3	Diversified electric power demand profile	8
4	Series heat-pump thermal subsystem block diagram	10
5	Series heat-pump thermal subsystem control strategy	10
6	Parallel heat-pump thermal subsystem block diagram	11
7	Parallel heat-pump thermal subsystem control strategy	11
8	Utility-interactive inverter electrical subsystem block diagram	13
9	DC electrical subsystem with storage block diagram	13
10	Heat-pump heating-mode performance	14
11	Heat-pump cooling-mode performance	15
12	Combined photovoltaic/thermal collector performance	17
13	Time-of-use utility rate schedule	20
14	Sample system economics summary	24
15	New York residence (with utility-interactive electrical subsystem) system performance results	25
16	New York residence (with DC electrical subsystem with storage) system performance results	27
17	New York residence (with utility-interactive electrical subsystem) system economic forecasts	29
18	New York residence (with DC electrical subsystem with storage) system economic forecasts	30
19	New York residence system economic forecasts for separate thermal and photovoltaic collector systems	31
20	Fort Worth residence system performance results	32
21	Fort Worth residence system economic forecasts	34
22	Two-stage cascade heat pump configuration	37
23	Carrier Corporation's Solaround system	38
24	Series heat-pump configuration with preheating of return air	41
25	Parallel heat-pump configuration with preheating of return air	42
26	Dual-mode heat-pump configuration with preheating of return air	43

1.0 INTRODUCTION

Since October 1977, MIT Lincoln Laboratory has been researching combined photovoltaic/thermal (PV/T) solar collectors to assess their potential for use in meeting residential energy demands. This report presents the results of a conceptual design study using computer simulations to determine the physical and economic performance of the most desirable PV/T collector heat-pump solar systems for a single-family residence.

1.1 Objectives

The objectives of this design study were:

- To identify "reasonable" residential PV/T heat-pump system configurations.
- To predict the performance of such systems in meeting residential heating, cooling and electric power demands.
- To compare system performances in northern and southern climates.
- To determine the most desirable systems for each of the two climates.

All economic evaluations were based on anticipated mid-1980's photovoltaic technology and prices and on 1986 system installation.

1.2 Summary and Conclusions

The TRNSYS simulation program, developed by the University of Wisconsin, was used to predict system energy flows in PV/T heat-pump systems in both New York and Fort Worth. The total auxiliary energy required by each system to meet the annual residential space heating, space cooling, hot water and diversified electric loads was calculated.

Two thermal subsystems were studied: a series or solar-source heat pump and a parallel or ambient-air-source heat pump. Two electric subsystems were studied: a utility-interactive DC-AC inverter subsystem which channels solar energy in excess of instantaneous on-site demands to the utility, and a DC subsystem with on-site electric energy storage and a "consume-only" utility connection. Four systems may be configured by permuting these thermal and electrical subsystems. The primary independent variable in all four systems, the total collector area, was varied from 0 to 100 square meters.

Economic analyses used TRNSYS performance results and assumptions for component costs, mortgage rates, tax marginal brackets, general inflation rate, energy escalation rate, and tax incentives to calculate the predicted levelized annual cost of owning and operating the solar system for its assumed 20-year lifetime beginning in 1986.

The results of this study show that:

- Systems employing on-site electrical storage batteries are not economically competitive with utility-interactive systems for a 0.5 utility energy buy-to-sell ratio.
- For the New York (northern) residence, the parallel heat-pump system configuration meets a greater percentage of the total residential loads with solar energy than the series heat-pump configuration for PV/T collector areas less than ~75 square meters.
- A parallel heat-pump system utilizing ~40 square meters of PV/T collectors and providing ~45% of the total residential energy demands represents the most economical PV/T system option of those studied for the New York residence.
- Separate thermal collectors and photovoltaic collectors result in systems with costs comparable to those using combined PV/T collectors in the New York residence.
- Due to the availability of low-cost electrical energy during the heating season in the Fort Worth (southern) residence, PV/T collector systems are not cost competitive in this location.
- The most economical system option for the Fort Worth residence consists of a parallel heat-pump system with ~35 m² of photovoltaic collectors, which provides ~48% of the total residential energy demands.

2.0 ANALYSIS METHODOLOGY

Figure 1 illustrates the general procedure used to evaluate the residential systems considered in this study. Hourly meteorological data and hourly residential heating and cooling demands were obtained for locations representative of the northern and southern regions of the United States. These data are based upon SOLMET weather data. Characteristic domestic hot water and diversified electric power loads were also defined for each location.

Residential photovoltaic/thermal system concepts were identified and the TRNSYS program was used to predict each system's performance. Simulations utilized a one-year period of weather data and load information to calculate the total auxiliary energy required to meet the annual space heating, space cooling, domestic hot water and electric power demands of the residence. Systems with combined photovoltaic/thermal, simple photovoltaic and simple thermal collectors were considered. The primary independent variable in the study was the total collector area, which was varied from 0 to 100 square meters.

An economic analysis calculated the levelized annual cost of owning, operating and maintaining the photovoltaic power system. This quantity includes the costs of borrowed capital, operation and maintenance, and auxiliary energy. Assumptions were made for the homeowner's mortgage rate and tax bracket as well as for the general inflation rate and energy escalation rate. The component costs and performance assumed are consistent with United States Department of Energy goals for photovoltaic devices. The levelized annual system cost is based upon a 20-year system lifetime beginning in 1986.

The ranking of system concepts was based upon the calculated levelized annual cost.

2.1 Meteorological and Heating/Cooling Data

The hourly solar and meteorological data used in this study are from SOLMET tapes for New York (1958) and Fort Worth (1960). Hourly space-conditioning loads were calculated for an 1800-ft² single-family detached residence using this weather data and the National Bureau of Standards Load Determination Program (NBSLD) (1). The loads and weather data, available on magnetic tape, are listed in Table 1.

Figure 1. Procedure flowchart.

TABLE 1
METEOROLOGICAL AND RESIDENTIAL SPACE
CONDITIONING LOAD QUANTITIES ON MAGNETIC TAPE

Hourly Data	Units
Direct normal insolation	(KJ/hr-m ²)
Total horizontal insolation	(KJ/hr-m ²)
Diffuse horizontal insolation	(KJ/hr-m ²)
Ambient dry bulb temperature	(°C)
Dew point temperature	(°C)
Wind speed	(m/s)
Atmospheric pressure	(kPa)
Solar zenith angle	(deg)
Solar azimuth angle	(deg)
Solar time	(hours-minutes)
Local standard time	(hours-minutes)
Year-month-day	
Sensible heat load	(KJ/hr)
Latent heat load	(KJ/hr)
Conditioned space dry bulb temperature	(°C)
Conditioned space relative humidity	(%)

A summary of the monthly heating and cooling loads used in the system simulations is shown in Table 2. The assumptions used in calculating the hourly space-conditioning loads resulted in a high annual heating load and a small cooling load for the New York residence. To obtain loads more indicative of energy-conscientious construction, shown in Table 2, the hourly heating loads from the data tape were halved and the cooling loads were doubled.

TABLE 2
RESIDENTIAL HEATING AND COOLING DEMAND
(kilowatt-hours thermal)

Month	Fort Worth		New York	
	Heating	Cooling	Heating	Cooling
January	1501	2	2165	0
February	1464	7	2256	0
March	1356	27	1790	0
April	154	100	1115	0
May	118	289	883	0
June	0	2487	84	50
July	0	2980	0	558
August	0	3025	0	356
September	0	2175	69	106
October	91	294	1010	0
November	479	41	1318	0
December	<u>1576</u>	<u>0</u>	<u>2350</u>	<u>0</u>
TOTAL	6739	11427	12990	1070

2.2 Residential Loads

The assumed hot water demand profile adopted from Reference 2 is shown in Figure 2. A daily total of 227 kilograms at 65°C is assumed for a four-person family. Due to seasonal temperature variations in the supply water, the energy

Fig. 2. Domestic hot water demand profile.

required to meet this demand changes. Table 3 shows the monthly supply water temperature assumed for the New York and Fort Worth locations.

A daily diversified (non-heating or cooling) electric power demand profile adopted from Reference 2 is shown in Figure 3. This load was assumed equal for both locations. A daily total of 26.7 kWh is assumed for lights and appliances; no seasonal variation was assumed.

2.3 Residential Energy System Concepts

Photovoltaic/thermal collectors may be configured into a variety of residential energy systems by selecting different thermal and electrical subsystems. Two thermal subsystem heat pump configurations are of interest: a series or solar-source heat pump, and a parallel or ambient air-source heat pump. Two electrical subsystem options were considered: a utility-interactive DC-to-AC power inverter with no on-site electrical storage, and a DC subsystem utilizing lead-acid batteries for storage. In addition to the four solar system options which may be configured by combining the thermal and electrical subsystems, a non-solar or conventional system was simulated

TABLE 3

MONTHLY SUPPLY WATER TEMPERATURE

Month	Supply Water Temperature (°C)
January	2.22
February	1.67
March	2.22
April	3.89
May	8.33
June	12.22
July	14.44
August	15.56
September	16.11
October	13.89
November	8.89
December	7.22

Fig. 3: Diversified electric power demand profile.

for comparison. The conventional system consists of an ambient-air-source heat pump with electrical resistance heating as backup. The hot water is heated electrically.

A system consists of both electrical and thermal subsystems, and an array of photovoltaic/thermal collectors. For comparison, several simulations using arrays of separate photovoltaic and thermal collectors were made. The subsystems considered are described below.

2.3.1 Series, or Solar-Source; Heat-Pump Thermal Subsystem

A series heat pump is one which operates in the heating mode with thermal energy supplied to its evaporator by the solar thermal storage tank. The series subsystem is shown in Figure 4. The heat pump in this system is designed to operate with evaporator temperatures in the range of 0 to 40°C.

Thermal energy from the combined photovoltaic/thermal collector array is stored in a water tank. When the storage temperature is above 40°C, the water may be circulated through a heat exchanger in the room-return air duct to provide energy directly to the space-heating load. In this mode, the heat pump is bypassed and the system resembles a conventional solar-thermal heating system. The heat pump may operate in the solar-source mode whenever the storage tank temperature is between 40°C (above which direct heating is possible) and 0°C (at which the water would freeze). Electrical resistance heating is provided when the storage tank approaches its freezing point. This control strategy is shown in Figure 5. In the cooling mode, the heat pump rejects heat with an outdoor-air heat exchanger.

Preheating of the hot water supply is accomplished by heat exchange between the main storage tank and the preheat storage tank whenever a 5°C difference in tank temperatures exists.

A potential advantage of the series heat-pump configuration over a parallel configuration is that the tank temperature is often warmer than the outdoor air, thereby resulting in an increased heating-mode coefficient-of-performance. Furthermore, the lower temperature of the thermal storage tank, relative to the parallel heat-pump configuration, yields improved thermal and electrical PV/T collector efficiencies. In actual operation, a series heat-pump benefits

Figure 4. Series heat-pump thermal subsystem.

Figure 5. Series heat-pump thermal subsystem control strategy.

additionally from improved evaporator heat transfer and elimination of the defrost cycle problems.

2.3.2 Parallel, or Ambient-Air-Source, Heat-Pump Thermal Subsystem

A parallel heat pump, shown in Figure 6, operates in the heating mode with thermal energy supplied to its evaporator by outdoor ambient air. As before, collected thermal energy is stored in a water tank and the most efficient mode of space heating is direct heating from this tank. The heat pump supplies auxiliary thermal energy when the tank temperature drops below 40°C. Electrical resistance heating is provided when neither the thermal storage nor the heat pump are capable of satisfying the heating demand. The control strategy for this system is shown in Figure 7.

Fig. 6. Parallel heat-pump thermal subsystem.

Fig. 7. Parallel heat-pump thermal subsystem control strategy.

Space cooling is accomplished by the heat pump which rejects heat to the outdoor air. Domestic hot water preheating is accomplished by heat exchange between the main storage tank and the preheat storage tank whenever a 5°C difference in tank temperatures exists. The hotter the main storage tank, the greater the fraction of the domestic hot water demand provided by solar energy.

2.3.3 Utility-Interactive Inverter Electrical Subsystem

The simplest residential electrical subsystem consists of a utility-interactive DC-to-AC power inverter with the capability to track the maximum power point of the photovoltaic array. This inverter allows photovoltaic array power in excess of the instantaneous demand to be directed to the utility. When auxiliary energy is required to meet the loads, it is provided by the utility through the interactive inverter. This electrical subsystem, depicted in Figure 8, assumes no on-site storage of electric energy.

2.3.4 DC Electrical Subsystem with Storage

A second electrical subsystem considered uses on-site electrical storage. Excess electric energy generated by the solar array is stored in batteries or is dissipated in an outdoor resistive load to prevent overcharging of the batteries. Auxiliary energy is provided to the DC loads by an AC-to-DC rectifier. This system is depicted in Figure 9.

2.4 Component Models

TRNSYS system performance simulations used a time step of 0.25 hours and covered the entire year (8760 hours). Among the subroutines added to the TRNSYS library were: a combined photovoltaic/thermal collector, a lead-acid battery, a power-dump battery-charge controller, and an energy time-of-use calculator to sum auxiliary energy use by electric utility time-of-use pricing periods.

The total annual auxiliary energy used during the utility peak, shoulder and off-peak hours was calculated in each simulation. Other quantities calculated included average collector efficiency, average tank temperature, and heat-pump energy flows.

Figure 8. Utility-interactive inverter electrical subsystem block diagram.

Figure 9. DC electrical subsystem with storage block diagram.

2.4.1 Heat Pumps

Two heat pump models were used in the simulations. The parallel heat-pump mathematical model was derived from an existing high-efficiency two-speed device. The heating coefficient-of-performance of this heat pump varies from 1.2 to 3.6 over the designed evaporator-source temperature range of -25°C to 20°C . A plot of the performance of this unit is shown in Figure 10.

The model used for the series heat pump reflects the anticipated performance (Figure 10) of a device being developed. The heating-mode coefficient-of-performance varies from 3.2 to 8.1 over the evaporator-source temperature range of 2° to 40°C . Existing parallel heat pumps are poorly suited to the elevated evaporating temperatures consistent with series operation (3). Operation of a parallel heat pump at evaporator temperatures in the range of 20 – 40°C generally results in high refrigerant vapor densities and mass flow rates which cannot be accommodated by the heat-pump compressor, heat exchangers or expansion valve. Forced off-design operation in this temperature range results in coefficients-of-performance that are significantly lower than potentially attainable. Consequently, the U. S. Department of Energy has funded the development of heat pumps optimized for the higher-than-ambient

Fig. 10. Heat-pump heating-mode performance.

evaporating temperatures inherent in the series system.

The cooling-mode performance of each heat pump is shown in Figure 11.

Fig. 11. Heat-pump cooling-mode performance.

2.4.2 Photovoltaic/Thermal Collector

A modified Hottel, Whillier, Bliss collector model was used to simulate the dynamic thermal and electrical performance of a flat-plate combined photovoltaic/thermal (PV/T) collector (4). The PV/T collector model assumed characteristics shown in Table 4.

TABLE 4

COMBINED PHOTOVOLTAIC/THERMAL COLLECTOR
PERFORMANCE CHARACTERISTICS

Single glazed, transmissivity $\tau = 0.88$
Plate absorptivity, $\alpha = 0.75$
Plate emissivity, $\epsilon = 0.75$
Bottom and edge heat loss
coefficient, $U_{be} = 1.06 \text{ KJ/hr-}^\circ\text{C-m}^2$
Collector efficiency factor, $F' = 0.9$
Encapsulated photovoltaic cell
efficiency at 25°C , $\eta_r = 0.12$
Temperature coefficient of photovoltaic
cell efficiency, $B_r = 5 \times 10^{-3}$
Geometrical solar cell packing density,
 $P_f = 0.9$

The approximate thermal and electrical performance of this collector is shown in Figure 12. The coolant liquid was assumed to be an antifreeze solution ($C_p = 3.35 \text{ KJ Kg}^{-1}^\circ\text{C}^{-1}$, for water $C_p = 4.186 \text{ KJ Kg}^{-1}^\circ\text{C}^{-1}$). The liquid mass flow rate through the collectors was varied from 50 to 100 kg/hr-m^2 . Collector tilt angle was assumed to be 50° for the New York residence and 40° for the Fort Worth residence.

A simple solar thermal collector was also modelled. Its characteristics were assumed to be similar to those of the PV/T collector with the exceptions of higher absorptivity, 0.9, and lower emissivity, 0.6. A photovoltaic collector was modelled assuming the same cell characteristics and packing factor as

in the PV/T collector, but without the cover-glazing-related optical losses and thermal gains.

Figure 12. Combined photovoltaic/thermal collector performance.

2.4.3 Electrical Subsystem Components

A simple battery model which assumes a constant 84% throughput energy efficiency was used. The storage capacity used in a system was varied from 0.2 to 0.5 kilowatt-hours per square meter of PV/T (or PV) collectors. To prevent battery overcharging, a resistive power dump and appropriate controls were used. Auxiliary electric power in the DC subsystem was provided through a battery charger with constant efficiency of 0.95.

The utility-interactive inverter was assumed to have a constant efficiency of 0.90, typical of current technology hardware. The inverter's assumed photovoltaic-array maximum-power-point tracking capability is incorporated in some currently available units.

2.4.4 Thermal Subsystem Components

The collector loop containing an antifreeze solution was thermally linked to the main storage tank by a constant-effectiveness (0.75) heat exchanger. The main storage tank was assumed to be 1.5 meters high regardless of its volume, and to have a loss coefficient of $0.42 \cdot \text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$.

The domestic hot water subsystem consisted of a 227-liter preheat tank which was thermally linked to the main tank by a constant-effectiveness (0.7) heat exchanger.

Parasitic power requirements were assumed for the pumps and fans in the thermal subsystem, amounting to 74 watts each in the collector and storage tank loops, 37 watts in the domestic water preheat loop, and 370 watts each for the air-space blower and the outdoor fan/coil unit.

2.5 Economic Analysis

A life-cycle cost analysis was made for each system simulated. This analysis utilized the total annual auxiliary energy prediction calculated by TRNSYS and the economic assumptions listed in Table 5. The levelized annual system cost includes the costs of capital, system operation and maintenance, and auxiliary energy. The basic component costs assumed in this analysis are shown in Table 6.

TABLE 5
SYSTEM ECONOMIC ASSUMPTIONS

System lifetime, t	20 years
Mortgage rate, i	9%
General inflation rate, j	6%
Fuel inflation rate, j_e	10%
Homeowners tax bracket, T_{inc}	35%
System installation date	1986
Federal tax credit	30% (up to \$2000), 20% (next \$8000)

TABLE 6
COMPONENT PRICE ASSUMPTIONS
(1986 price, 1975\$s)

Combined PV/T collector (\$/m ²)	125
Thermal collector (\$/m ²)	75
Photovoltaic module (\$/m ²)	75
Air-to-air heat pump (\$)	1500
Water-to-air heat pump (\$)	1850
Thermal storage tank (\$/kg)	0.20
DC-AC inverter (\$/kVA)	150
AC-DC rectifier (\$/system)	900
Storage batteries (\$/kWh)	65
Battery related cost (\$/system)	1000
DC system related cost (\$/system)	600
Thermal system costs (\$/system)	1000

A time-of-use utility rate (TOUR) structure was assumed in calculating the cost of auxiliary energy. Data for two experimental TOUR schedules, Figure 13, show the seasonal and daily variation in the per-kWh price of energy.

Fig. 13. Time-of-use utility rate schedule.

The monthly billing for auxiliary energy consists of the fixed amount plus the per-kWh amount. Over the system lifetime, this fixed amount was increased at the general inflation rate and the per-kWh charge was increased at the average of the fuel and general inflation rates. Half the per-kWh cost to the consumer for electrical energy under a time-of-use rate schedule is assumed to be for fuel and half for transmission and distribution. This yields a net increase in the per-kWh energy cost of 8% per year.

The levelized annual system cost reflects the annual cost of owning, operating and maintaining the photovoltaic system over its lifetime. The first step in calculating this quantity is to determine the current dollar* after tax cash flow for each year of system operation. This quantity is equal to the sum of net capital cost, operation and maintenance costs, auxiliary energy cost and net component replacement cost.

In the following definitions, C_s represents costs in 1975\$ and E_s represents energy measured in kilowatt-hours:

C_e = auxiliary energy cost in year n

C_f = energy related fixed cost in year n

C_{net} = net after tax annual capital cost in year n

C_{om} = operation and maintenance cost in year n

$CRF(i, t)$ = capital recovery factor $1 / \sum_{n=1}^t (1+i)^{-n}$

C_s = total initial solar equipment cost

C_{sav} = salvage value of a component

C_{sr} = salvage value credit or replacement cost in year n

E_{opp} = annual auxiliary energy purchased during utility off-peak period

*Current Dollars: The number of dollars associated with a specific real value at a given time, subject to change at the general inflation rate. Food costs are always in current dollars.

Constant Dollars: A number of dollars which does not change regardless of the effect of inflation. Mortgage payments are in constant dollars.

- E_{op} = annual photovoltaic electric energy sold back during utility off-peak period
 E_{pkp} = annual auxiliary energy purchased during utility peak period
 E_{pks} = annual photovoltaic electric energy solar back during utility peak period
 E_{shp} = annual auxiliary energy purchased during utility shoulder period
 E_{shs} = annual photovoltaic electric energy sold back during utility shoulder period
 n = year of system operation
 P_n = remaining principle in year n
 T_{ann} = net after tax annual current dollar cash flow
 η_s = energy sellback-to-buy ratio

The annual cash flow is, then

$$T_{ann} = C_{net} + C_{om} + C_e + C_{sr}, \quad (1)$$

where

$$C_{net} = C_s \times CRF(i, t) - T_{inc} \times i \times P_n, \quad (2)$$

and

$$C_{om} = .02 \times C_s (1 + j)^n, \quad (3)$$

$$C_e = C_{pk} (E_{pkp} - \eta_s E_{pks}) + C_{sh} (E_{shp} - \eta_s E_{shs}) + C_{op} \quad (4)$$

$$(E_{ops} - \eta_s E_{ops}) + C_p,$$

and

$$C_{sr} = -C_{salv} + C_{rep}. \quad (5)$$

The cost of energy is based upon the time-of-use rate schedule and an assumed sellback-to-buy rate ratio of 0.5. The annual fixed cost, C_f , associated with purchase of energy is the sum of the monthly charges, including city and state taxes where applicable.

A salvage value of 15% of the original cost is assumed for batteries after ten years of service and for heat pumps after 20 years of service. A 10% salvage value is assumed for solar collectors after 20 years. These credits and the battery replacement cost after 10 years are included in C_{sr} for the appropriate year.

Operation and maintenance charges are assumed to be 2% of the total initial cost annually. This cost escalates at the general inflation rate.

The 1986 dollar present value, PV_{86} , of all yearly expenditures over the system lifetime is:

$$PV_{86} = \sum_{n=1}^{20} T_{ann} / [1 + i(1 - T_{inc})]^n. \quad (6)$$

The levelized annual cost, LAC, is the present value multiplied by the capital recovery factor

$$LAC = PV_{86} \times CRF(i', t), \quad (7)$$

where

i' = effective after tax discount rate

$$= [i(1 - T_{inc}) - j] / (1 + j). \quad (8)$$

M.I.T. LINCOLN LABORATORY
RESIDENTIAL PV/T SYSTEM ECONOMICS SUMMARY

C74-808

NY PAR AC
COLLECTOR AREA (SQ. M.) = 50.00
THERMAL STORAGE (KG/UNIT AREA) = 50.00
ELECTRIC STORAGE (KWH/UNIT AREA) = 0.0
ENERGY INFLATION RATE = 0.10
ENERGY BUY-TO-SELL RATIO = 0.50

ENERGY PURCHASED ON PEAK (KWH) = 1591.00
ENERGY PURCHASED ON SHOULDER (KWH) = 3702.00
ENERGY PURCHASED OFF-PEAK (KWH) = 8691.00
ENERGY SOLD ON PEAK (KWH) = 401.00
ENERGY SOLD ON SHOULDER (KWH) = 350.00
ENERGY SOLD OFF PEAK (KWH) = 318.00

***** YEAR-END CASH FLOWS IN CURRENT YEAR DOLLARS *****

YEAR	OUTSTANDING PRINCIPLE	YEAR END PRINCIPLE	PAYMENT INTEREST	O & M	AUXILIARY ENERGY	SALVAGE RETURN	TOTAL ANN COST	AFTER TAX COST
1986	19362.44	378.47	1742.62	327.25	1889.02	0.0	4397.34	1587.44
1987	18983.96	412.54	1708.56	410.48	2037.97	0.0	4569.55	3971.55
1988	18571.42	449.67	1671.43	435.11	2198.72	0.0	4754.92	4169.92
1989	18121.75	490.14	1630.96	461.22	2372.18	0.0	4954.49	4383.65
1990	17631.62	534.25	1586.84	488.89	2559.37	0.0	5169.35	4613.96
1991	17097.37	582.33	1538.76	518.22	2761.39	0.0	5400.70	4862.13
1992	16515.04	634.74	1486.35	549.32	2979.40	0.0	5649.80	5129.58
1993	15880.29	691.87	1429.23	582.27	3214.68	0.0	5918.04	5417.81
1994	15188.42	754.14	1366.96	617.21	3468.59	0.0	6206.89	5728.46
1995	14434.29	822.01	1299.09	654.24	3742.63	0.0	6517.96	6063.28
1996	13612.27	895.99	1225.10	693.50	4038.38	0.0	6852.96	6424.18
1997	12716.28	976.63	1144.46	735.11	4357.56	0.0	7213.76	6813.20
1998	11739.65	1064.52	1056.57	779.21	4702.05	0.0	7602.36	7232.56
1999	10675.12	1160.33	960.76	825.96	5073.86	0.0	8020.91	7684.64
2000	9514.79	1264.76	856.33	875.52	5475.15	0.0	8471.76	8172.04
2001	8250.02	1378.59	742.50	928.05	5908.26	0.0	8957.40	8697.52
2002	6871.43	1502.66	618.43	983.73	6375.73	0.0	9480.55	9264.10
2003	5368.76	1637.90	483.19	1042.76	6880.29	0.0	10044.13	9875.02
2004	3730.86	1785.32	335.78	1105.32	7424.87	0.0	10651.28	10533.76
2005	1945.54	1945.99	175.10	1171.64	8012.67	-330.00	10975.40	10914.12

JAN. 1, 1986 PRESENT VALUE

1986 DOLLARS 67671.75
1975 DOLLARS 35649.00

LEVELIZED ANNUAL COST

1986 DOLLARS 3333.61
1975 DOLLARS 1756.12

DISCOUNT RATE = 0.0585
EFF. DISCOUNT RATE 1' = -0.0014
MARGINAL TAX BRACKET = 0.3500
MORTGAGE RATE = 0.0900

GENERAL INFLATION RATE = 0.0600
ENERGY ESCALATION RATE = 0.1000
CRF(I', T) = 0.0493
COLLECTOR COST (\$/S.M.) = 125.00

Fig. 14. Sample system economics summary.

The levelized annual cost may then be expressed in constant 1975 dollars* by using the general inflation rate, j.
A sample economics summary is shown in Figure 14 for a New York location parallel heat-pump system with 50 square meters of PV/T collectors.

*A 1975\$ quantity may be converted to 1980\$ using: 1980\$ = 1.4 x 1975\$.

3.0 RESULTS

This Section presents the results of performance and economic analysis for both the New York and Fort Worth residences.

3.1 New York Residence System Performance Results

Figure 15 shows the percentage of the total electrical and thermal demand provided by solar energy, as a function of collector area for three systems in the New York residence.

Fig. 15. New York residence (with utility-interactive electrical subsystem) system performance results.

Each system shown utilized the AC utility-interactive subsystem. The annual percent solar is calculated as:

$$f_s = \left[1 - \frac{E_p - E_s}{Q_{sh} + Q_c + Q_{dhw} + E_{div}} \right] \times 100$$

where

E_{div} = diversified electrical load

E_p = electrical energy purchased

E_s = electrical energy sold to the utility

f_s = percent of the total electrical and thermal demand provided by solar energy.

Q_c = space cooling thermal load

Q_{dhw} = domestic hot water thermal load

Q_{sh} = space heating thermal load

The conventional system, utilizing a parallel heat pump without solar collectors, provides approximately 27% of the load by solar energy because the heat pump extracts energy from the outdoor air (indoor air in the cooling mode) at a coefficient-of-performance greater than 1. As the collector area approaches zero, both parallel heat-pump systems approach the conventional system performance, as expected. The series heat pump without collectors, however, relies completely upon electrical resistance for space heating and, therefore, solar sources supply virtually none of the residential loads in this case (the small cooling load is still met by the heat pump at COP greater than 1).

Even at modest collector areas there is often insufficient stored thermal energy available to the heat-pump evaporator to allow full-time series heat-pump heating. When this "starvation" condition occurs, the space-heating load is met by electrical resistance heating at a COP of 1. Consequently the potentially high COP advantages of the series heat pump are realized only with

collector areas greater than 75 square meters. At these large PV/T collector areas, the total auxiliary energy required by the series heat-pump system is slightly less than that required by the parallel heat-pump system. Both the series and parallel heat-pump configurations utilizing PV/T collectors provide a greater percentage of the total load than the parallel configuration using simple photovoltaic collectors. This is due to the inability of the PV system to accomplish either direct space heating or domestic hot water preheating.

Figure 16 shows the percent solar as a function of collector area for a parallel heat pump configuration using the DC electrical subsystem. This system using PV/T collectors provides approximately 10 percent less of the total demand than the comparable system using the AC utility-interactive subsystem. Greater amounts of auxiliary energy are required for the DC system because: the throughput efficiency of the storage batteries is .84, whereas the AC subsystem utilizes the utility grid as storage at an effective efficiency of 1.0; all auxiliary energy is provided through a battery charger with an efficiency of 0.95; at large collector areas, some PV energy is dissipated to prevent battery overcharging.

Fig. 16. New York residence (with DC electrical subsystem with storage) system performance results.

Table 7 lists the percent solar for the parallel heat-pump configuration with the AC utility-interactive subsystem utilizing a solar array consisting of separate photovoltaic and thermal collectors in the New York residence.

TABLE 7

ENERGY PERFORMANCE OF A NEW YORK RESIDENCE
UTILIZING SEPARATE PHOTOVOLTAIC AND
THERMAL COLLECTORS

Total	Collector Area (m ²)		Percent Solar
	Photovoltaic	Thermal	
50	25	25	51.1
75	25	50	54.4
75	50	25	62.1
100	25	75	56.6
100	50	50	65.4
100	75	25	73.1

For a fixed total collector area, the systems utilizing PV/T collectors supply a greater percentage of the residential demands than any of the combinations of separate photovoltaic and thermal collectors. For example, the parallel heat-pump configuration using 75 m² of PV/T collectors results in 65.4 percent solar which is greater than that for both separate collector combinations in Table 7 using a total collector area of 75 m², (54.4 and 62.1).

3.2 New York Residence System Economic Forecasts

The economic forecasts for three systems in the New York residence are indicated in Figure 17, which shows the levelized annual system cost as a function of the total collector area. This figure reflects the component costs and economic assumptions listed previously. The most economical system for the New York residence is the parallel heat-pump configuration with

Fig. 17. New York residence (with utility-interactive electrical subsystem) system economic forecasts.

approximately 40 square meters of PV/T collectors, at a levelized annual cost of \$1740. Despite the reduced auxiliary energy required by the series heat-pump system at large collector areas, this system is consistently more expensive than the parallel heat-pump systems with equal collector areas since auxiliary energy savings are offset by the cost of the larger thermal energy storage found optimal for the series system.

Figure 18 shows the levelized annual cost for the parallel heat-pump configuration with the battery-storage electrical subsystem. The cost of this system using PV/T collectors is significantly greater than that of the corresponding utility-interactive parallel system due to the initial high cost of batteries and their protective housing.

Fig. 18. New York residence (with DC electrical subsystem with storage) system economic forecasts.

Table 8 lists the levelized annual cost for the parallel heat-pump configuration utilizing separate photovoltaic and thermal collectors.

Figure 19 shows the levelized annual cost of the PV/T parallel heat-pump system for three PV/T collector prices: \$100, \$125 and \$150/m². Also shown are the levelized annual system costs for a parallel system utilizing combinations of separate photovoltaic and thermal collectors (\$75/m² for each collector type). For a total collector area of 50 m² and a PV/T collector cost of \$100/m², separate collectors (25-m² PV and 25-m² thermal) and PV/T collectors result in virtually the same levelized annual system cost. A separate-collector parallel heat-pump system with more than 50 m² of available

TABLE 8

LEVELIZED ANNUAL COST OF A NEW YORK
RESIDENCE UTILIZING SEPARATE
PHOTOVOLTAIC AND THERMAL COLLECTORS

Total	Collector Area (m ²)		Levelized Annual System Cost (1975\$)
	Photovoltaic	Thermal	
50	25	25	1654.
75	25	50	1726.
75	50	25	1562.
100	25	75	1828.
100	50	50	1639.
100	75	25	1505.

Fig. 19. New York residence system economic forecasts for separate thermal and photovoltaic collector systems.

roof can result in a lower levelized annual cost than the least-cost PV/T collector system; this, however, requires large roof area.

3.3 Fort Worth System Performance Results

Figure 20 shows the percent solar as a function of collector area for three systems in the Fort Worth residence. All systems shown used the utility-interactive AC subsystem. No DC systems were considered for the Fort Worth location due to the high cost for these systems found in the New York residence simulation. The trends in these curves are the same as those for the New York residence. In the Fort Worth location, however, which is characterized by a high cooling demand and moderate heating requirement, the benefits of the series system over the parallel systems are shown for PV/T collector areas above approximately 55 m². At zero collector area, both parallel systems approach the performance of the conventional non-solar system. The three systems shown all meet more than 50% of the total residential demands given collector areas larger than 40 square meters.

Fig. 20. Fort Worth residence system performance results.

Table 9 lists the percent solar for the parallel heat-pump system using separate photovoltaic and thermal collectors. For a fixed total collector area, the systems utilizing combined photovoltaic/thermal collector systems provide a greater percentage of the total load than any of the separate photovoltaic-combined photovoltaic/thermal collector systems.

TABLE 9
ENERGY PERFORMANCE OF A FORT WORTH RESIDENCE
UTILIZING SEPARATE PHOTOVOLTAIC AND THERMAL
COLLECTORS

Total	Collector Area (m ²)		Percent Solar
	Photovoltaic	Thermal	
50	25	25	58.3
75	25	50	60.4
75	50	25	70.6
100	25	75	61.6
100	50	50	72.7

3.4 Fort Worth Residence System Economic Forecasts

The economic forecasts for three Fort Worth residential systems are shown in Figure 21. The most economical system option in this location is a parallel heat-pump system with approximately 35 square meters of photovoltaic collectors. This system is the only one which results in a lower annual cost than a conventional non-solar system. The relatively inexpensive time-of-use rate electrical energy prices for the Fort Worth residence (Figure 13) show that all energy used during the heating season is charged at the off-peak rate. The availability of this low-cost electrical energy resulted in no cost-competitive PV/T systems for this location.

The economic forecasts for a parallel heat-pump system using separate collectors are given in Table 10. None of these separate collector systems results in a lower than conventional annual cost.

Fig. 21. Fort Worth residence system economic forecasts.

TABLE 10

LEVELIZED ANNUAL COST OF A FORT WORTH RESIDENCE UTILIZING SEPARATE PHOTOVOLTAIC AND THERMAL COLLECTORS

Total	Collector Area (m ²)		Levelized Annual System Cost (1975\$)
	Photovoltaic	Thermal	
50	25	25	938.
75	25	50	1069.
75	50	25	972.
100	25	75	1206
100	50	50	1103.

4.0 CONCLUSIONS

Designs for the most economical solar-energy system for each of the two climate regions have been based upon system-simulation results.

In areas of high utility energy prices and residential heating loads, the most economical energy systems:

- Provide approximately 50% of the total residential thermal and electrical demands.
- Utilize approximately 4-kW electric peak (40 m^2) of combined photovoltaic/thermal solar collectors,
- Or may utilize a combination of separate photovoltaic and thermal collectors (25 m^2 thermal, $50\text{--}75 \text{ m}^2$ PV) for large available roof areas).
- Utilize a utility-interactive DC-AC inverter without on-site electric energy storage.
- Provide auxiliary thermal energy with a parallel heat pump.

In areas where low utility energy prices prevail and heating loads are small relative to large air conditioning loads, the least-cost system option:

- Utilizes approximately 3.5-kW electrical peak (35 m^2) of photovoltaic modules.
- Utilizes a utility-interactive DC-AC inverter without on-site storage of electrical energy.
- Provides space cooling and space heating with an ambient-air-source heat pump.

5.0 HARDWARE CONSIDERATIONS

This Section presents specific hardware recommendations for a prototype residential PV/T system which MIT Lincoln Laboratory will assemble and evaluate for the U. S. Department of Energy. In the process of detailing the conceptual design, additional system configurations were identified, but were not found to warrant consideration. One such system is discussed briefly.

The remainder of the Section describes the commercially available heat-pump equipment which most closely meets the requirements of the recommended conceptual system design. The selection between competing manufacturers was usually resolved by schedule requirements. As such, alternative equipment may be available from other suppliers in the near future and no endorsement of the selected equipment is intended or implied.

5.1 Constraints on System Complexity

The series and parallel configurations were considered in detail in Section 2 primarily because of their relative simplicity and because they have been the subject of extensive analyses in connection with exclusively thermal systems (References 3, 5, and 6). The results of these analyses are consistent with the results given in Section 3. These previous analyses also show that for exclusively thermal systems, additional system components (such as a second heat pump or a third refrigerant coil) are not usually economically advantageous. For this reason, the system concepts discussed in Section 2.3 were limited to one heat pump, one thermal storage tank, and two heat-pump refrigerant coils.

In order to evaluate the improvements offered by more complex PV/T configurations, the TRNSYS program was applied to the cascade configuration shown in Figure 22. The system's annual coefficient-of-performance was used as a performance index. The cascade configuration is of interest because it reduces to the series, parallel, or dual-mode configuration, provided the appropriate operating procedure is specified. The dual-mode configuration is sometimes referred to as the three-coil configuration. The cascade configuration can be operated in such a way as to obtain a more favorable annual

Fig. 22. Two-stage cascade heat-pump configuration.

performance than the series, parallel, or dual-mode configurations. Using a fairly elaborate control strategy and an optimistic assumption concerning the capacity of the stage-one (air-to-water) heat pump, it was found that for the New York location the annual COP of the cascade configuration was at best only 5% higher than that of the parallel configuration at all collector areas below 100 m^2 . Therefore, even if the constraints concerning the number of system components were relaxed, no economic advantage would be gained because of the increased cost of the additional components.

An air-source solar-boostered heat pump in which the evaporator consists of a flat-plate collector is discussed in Reference 7. The flat-plate collector operates near ambient temperature and collects energy either from the ambient air or from solar insolation. This unit is undergoing commercialization as a swimming pool heater. In the residential application, obtaining energy directly from solar insolation requires a thermal storage tank on the condenser side of the heat pump. This thermal storage tank supplies water to heat the return air from the residence and this water must be warmer than the supply air. Heating the thermal storage tank to a temperature above the residential supply air introduces inefficiencies that are not present in the swimming pool

CARRIER CORPORATION'S SOLAROUND SYSTEM

Figure 23.

application. For this reason inclusion of the evaporator-collector alternative in the residential prototype is not recommended.

5.2 Hardware Availability and Cost

An important consideration in the design of a PV/T and heat-pump prototype system is the availability of the preferred components. Fortunately, this requirement also favors the parallel configuration. Efficient water-source heat pumps suitable for the series configuration are available, but the cost of one of the appropriate units is approximately twice the cost of a two-speed air-to-air heat pump of equivalent capacity. As a result of a recent Department of Energy hardware development contract, the Northrup Corporation has built prototype heat pumps suitable for series and dual-mode operation. However, future availability of this equipment is uncertain. Both Lennox Industries and the Carrier Corporation manufacture two-speed air-to-air heat pumps suitable for use in a parallel system. As yet, only the Carrier Corporation has made available the control and plumbing subsystems that permit effective incorporation of collectors, thermal storage tank, and heat pump into a unified parallel system.

5.3 Carrier Corporation's "Solaround" System

The name "Solaround" is a trademark of the Carrier Corporation and is used to designate the combined solar collector and heat-pump system offered by this company (Figure 23). This system is similar to the exclusively thermal parallel systems considered in References 5 and 6 and in Section 2.3.2 of this report. There are, however, some interesting differences that are discussed in the following Sections.

5.3.1 Variable-Speed Compressor

Carrier recommends that a single-speed (3500 rpm) heat-pump compressor be used in the Solaround system. The simulations discussed in Sections 2 and 3 of this report confirm that a PV/T system benefits from the availability of a lower compressor speed. For this reason it is recommended that the single-speed heat pump (Carrier series 38HQ) be replaced with a two-speed heat pump (Carrier series 38TQ, 1750 and 3500 rpm).

5.3.2 Collector Fluid

Carrier recommends the use of a Glycol system ".... in areas where prolonged periods of subfreezing temperatures occur." The use of Glycol requires an additional heat exchanger and liquid pump. With proper installation, a plain water system is as reliable and efficient even in a northern climate. Proper installation includes fail-safe drain down of the water from the collectors to the storage tank when the circulating pump stops operating. Carrier's recommendation may be based on a concern about the non-uniformity of field installation practices. Both the series and parallel simulations discussed earlier in this report assumed that Glycol was the collector liquid and that the required additional heat exchanger and liquid pump were present in the system. It is now recommended that plain water be used as the collector liquid in the prototype system.

5.3.3 Tri-X Coil

The Solaround system includes an indoor heat exchanger called a Tri-X Coil which accommodates both circulating water and refrigerant in separate tubes. This offers the significant advantage of off-peak cooling of storage water. Not only does this avoid high summer daytime utility rates, but it also permits better humidity control since cooling need not be limited to intermittent heat pump operation. It is undesirable to attempt to control humidity exclusively by direct heat-pump operation unless the capacity of the heat pump and the cooling load are reasonably well matched. This is not likely to occur in the case of a northern residence because the heat-pump's capacity will be matched to the winter heating load.

The Tri-X Coil also makes it possible to heat the residence simultaneously, using stored thermal energy along with energy delivered by the heat pump. As pointed out in Reference 6, this improves the system's annual coefficient-of-performance provided the temperature of the circulating water does not fall too far below the cut-off temperature for heating exclusively from stored thermal energy. This "boosting" of the heat-pump's output will probably be consequential whenever it permits the heat-pump's compressor to remain operating at low speed. This boosting procedure was not incorporated in the simulations

discussed in Sections 2 and 3. The alternative of preheating the indoor return air by using stored thermal energy is considered in detail in Reference 6. The configurations examined in this Reference are shown in Figures 24, 25, and 26. In each case there are two alternatives for preheating: (1) using collector fluid (in this case, water) immediately after it returns from the collector, and (2) using water from the thermal storage tank. In Reference 6, it was found that preheating is a desirable option for all configurations, and that the first alternative is preferred except in the case of the parallel configuration. Before actually incorporating a separate preheating coil in the PV/T prototype system, it is advisable to carry out tests to determine if the Tri-X Coil functions adequately as a booster coil when hot water is circulated through it.

Fig. 24. Series heat-pump configuration with preheating of return air.

Fig. 25. Parallel heat-pump configuration with preheating of return air.

5.3.4 Desuperheating of the Compressor's Discharge Line

The Solaround system does not contain a heat-pump heat-reclamation device, or desuperheater, for heating domestic hot water. A desuperheater has not been included in previously published analyses of thermal systems, and was not included in the analyses discussed in Sections 2 and 3. The reason for this omission is that the coding of the TRNSYS computer program does not currently accommodate desuperheating devices and sufficient data describing their performance has not been available. A desuperheater will be incorporated in the prototype PV/T system because these devices can reclaim heat equal to between ten and fifteen percent of the energy throughput of the heat pump.

5.3.5 Resistance Heating

It is advantageous to install a low-watt density resistance heater in

C74-822

Fig. 26. Dual-mode heat-pump configuration with preheating of return air.

the water storage tank if surplus electric power cannot be directed into the utility grid under favorable terms. The simulations discussed in Sections 2 and 3 assume different sell-back credits and resistance heating of the water storage tank was not considered.

5.4 Modified Solaround System Inventory

The Carrier Corporation components listed in Table 11 will be included in the prototype PV/T system. The remaining components required by the Solaround system are included in Table 12. An important requirement of the water storage tank is that it be able to withstand water temperatures as high as 93°C. A fiberglass-reinforced plastic tank is recommended; the lining of the plastic tank must conform to NBS Product Standard No. PS 15-69.

TABLE 11

CARRIER CORPORATION COMPONENTS INCLUDED IN
PV/T PROTOTYPE SYSTEM

Component	Carrier Corporation Part Number
Heat-pump two-speed compressor section	38TQ-040-301
Heat-pump outdoor heat exchanger	38HQ-960-301
Tri-X indoor heat exchanger	28QX-042-001
Indoor fan section	40FS-200-311
10-kW indoor resistance heater	40FQ-920-121
Heat-pump desuperheater	38HQ-900-011
Thermostat package	34WA-900-011
Off-rate cooling control	34WA-900-021
Domestic hot water preheat accessory	34WA-900
Heat-pump stand	38RQ-900-061
Filter dryer	38CQ-900-091
Moisture eliminator package	28GS-660-023
Plain water pump package	34WA-367

TABLE 12

REMAINING COMPONENTS INCLUDED IN
PV/T PROTOTYPE SYSTEM

Component	Manufacturer	Part Number
80-gallon domestic hot water tank	Sepco	E-80-SNR-1-10
1000-gallon water storage tank	Owens-Corning	GIMAC
PV/T collector array	(to be determined)	
Inverter	Windworks	Gemini 8 kVA with Max. Power Tracking

5.5 Combined Photovoltaic/Thermal Collectors

Modifications to current combined photovoltaic/thermal collector designs show promise of improved electrical and thermal performance. Based upon analytical studies and one year of outdoor experimental testing of three prototype PV/T collectors, "second-generation" liquid combined PV/T collectors will be designed and constructed.

The basic liquid-cooled PV/T collector design envisioned incorporates one cover-glass spaced above PV cells which are bonded to an integral absorber heat exchanger. A PV/T collector of this design may be optimized by following the specific design recommendations detailed below.

(i) There exists an optimum cell-to-glass air gap spacing for which the thermal-conductance to heat-loss ratio is a minimum. This spacing, however, is critically dependent on the cell-to-glass temperature difference. For a calculated temperature difference of 8 to 17°C, corresponding to insolation values between 50 to 100 mw/cm², a cell-to-glass air-gap spacing of 1.5 cm is optimum.

(ii) Thermal losses through the collector-top cover glass are typically made up of 60% radiative losses and of 40% convective losses. The convective losses may be reduced by a series of crisscrossing grooves on the top glass cover. These grooves enhance the formation of recirculation zones in the ambient air flowing over the glass surface and therefore reduce the effective convective-heat-transfer coefficient.

(iii) The thermal resistance between the cells and the absorber plate must be kept as small as possible. This can be done by minimizing the electrical insulation thickness between cells and the absorber plate, taking care to avoid air gaps. The traditional insulation, silicone pottant, has a thermal conductivity, K, of 0.002 watts/cm°C. However, several high thermal conductivity, high di-electric strength, epoxies are available with K ranging from 0.008 to 0.016 watts/cm°C. Use of these epoxies in place of the silicone pottant would ensure a low thermal resistance between the cells and the thermal collector while insuring electrical isolation.

(iv) Heat resistance resulting from air gaps between the absorber plate and the liquid-carrying tubes can be minimized by making the tubes an integral part of the absorber plate. One such commercially available absorber plate design is referred to as a "Roll Bond" absorber plate. A rectangular section for these tubes, with a width-to-height ratio greater than 3, has a higher heat-transfer coefficient than a circular tube. The larger this ratio, the higher the heat-transfer coefficient.

(v) In the prototype PV/T collectors, the liquid flow is laminar. For higher heat transfer between the tube and liquid, the flow should be turbulent. Presuming a rectangular tube section, wires on the tube walls normal to the flow can be used to trip the laminar flow to turbulent flow. Further, the tube walls can be made rough to augment the heat transfer.

A variety of other devices of uncertain cost effectiveness could be used to enhance the transmission and absorption of insolation by the components of the collector. These include, 1) stippled top-glass surface to reduce reflection losses, 2) anti-reflective coating of bismuth oxide and magnesium oxide on the glass cover and 3) selective paint coatings for the thermal collector plate.

REFERENCES

1. "Detached Family House Load Tape," Available from National Bureau of Standards, Washington, DC 20234.
2. Chobotov, V. and Siegel, B., "Analysis of Photovoltaic Total Energy Systems for Single-Family Residential Applications," The Aerospace Corporation, ATR-78 (7694-02)-1, August 1978.
3. Andrews, J. W., Kush, E. A., and Metz, P. D., "A Solar-Assisted Heat Pump System for Cost-Effective Space Heating and Cooling," Brookhaven National Laboratory, BNL 50819, March 1978.
4. Evans, D. L., Facinelli, W. A., and Otterbein, R. T., "Combined Photovoltaic/Thermal System Studies," Arizona State University, Sand78-7031, August 1978.
5. Freeman, T. L., Mitchell, J. W., and Andit, T. E., "Performance of Combined Solar-Heat Pump Systems," Solar Energy, Vol. 22, pp. 125-135, 1979.
6. Jaster, H., et al., "Solar Assisted Heat Pumps for the Heating and Cooling of Buildings," work performed under Contract No. EG-78-C-03-1719 for the Department of Energy, General Electric Company, November 1978.
7. Charter, W. W. S., "Some Performance Characteristics of the Unimeld Air Source Solar Boosted Heat Pump System," 1979 ISES Conference, Atlanta, Georgia, May 1979.