A DESCRIPTION OF THE UNIVERSITY OF TEXAS AT ARLINGTON
SOLAR ENERGY RESEARCH FACILITY
PHOTOVOLTAIC/THERMAL RESIDENTIAL SYSTEM

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Abstract

The addition of a photovoltaic array to a solar-heated single-family residence at the University of Texas at Arlington permits the study of combined photovoltaic/thermal system operation. Equipment and construction details are presented.

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Fig. 1. University of Texas at Arlington Solar Energy Research Facility site plan.

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1.0 INTRODUCTION

The Solar Energy Research Facility (SERF) located on the University of Texas campus at Arlington (UTA), Texas, comprises a single-family residence equipped with several heating and cooling subsystems (Fig. 1). The 1550-square-foot test residence was built as a cooperative venture by the University of Texas, the Texas Electric Service Company, and the UTA Construction Research Center. MIT/Lincoln Laboratory became involved to study the addition of photovoltaic (PV) electric power to an existing structure that was heated and cooled by solar energy.

2.0 PHOTOVOLTAIC SUBSYSTEM

The PV subsystem at UTA/SERF is composed of 240 solar cell modules which are mounted on 20 adjustable array support frames arranged in a true east to west direction. These array support frames are divided into two equal rows. Each frame can be tilted from between 25 and 37.5 degrees from horizontal to permit seasonal adjustment. Solar Power Corporation manufactured the solar cell modules (type E-10008/Rev B) which together produce a total of 8 kW_{pk}. The PV subsystem began operation on November 1, 1978. Refer to Fig. 2 for the field cabling diagram. Figure 3 depicts the array wiring for the north subfield, which Fig. 4 does the same for the south subfield.

The 240 modules are divided into 24 subfield units, each containing ten series-connected modules. Each subfield unit is connected to a field junction box(s) which can provide switching and limited testing. In addition, each subfield unit can be switched on or off either manually or by means of a computer through the main control panel, as shown on Fig. 5. Figure 6 shows the DC array field schematic.

Fig. 2. Field Cabling Diagram.

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Fig. 3. North Subfield Array Wiring. (Sheet 1 of 5)

Fig. 3. North Subfield Array Wiring. (Sheet 2 of 5)

C00-4577-5-3C

Fig. 3. North Subfield Array Wiring. (Sheet 3 of 5)

Fig. 3. North Subfield Array Wiring. (Sheet 4 of 5)

C00-4577-5-3E

Fig. 3. North Subfield Array Wiring. (Sheet 5 of 5)

C00-4577-5-4A

Fig. 4. South Subfield Array Wiring. (Sheet 1 of 5)

Fig. 4. South Subfield Array Wiring. (Sheet 2 of 5)

Fig. 4. South Subfield Array Wiring (Sheet 3 of 5)

Fig. 4. South Subfield Array Wiring. (Sheet 4 of 5)

(SHEET 5 OF 5)

Fig. 4. South Subfield Array Wiring. (Sheet 5 of 5)

Fig. 5. Control/Data Acquisition System.

Fig. 6. Array field schematic.

The DC bus feeds into an 8-kW, PCU-2 Gemini inverter. The inverter output is 240 volts AC at 40 Amps which is directed to a 15-kVA isolation transformer that provides ground isolation for the inverter. The single-phase transformer output is connected to the test house AC bus via a 60-Amp circuit breaker located in the main circuit breaker panel.

Array performance data are recorded on disks in the data acquisition system shown on Fig. 5. MIT/Lincoln Laboratory supplied the PV modules, frames, DC/AC inverter, and isolation transformer.

2.1 Support Structures

Support frames for the two collector banks are mounted on 44 footings as shown on Fig. 7. The 8-inch-diameter piers were poured with concrete with a No. 3 deformed bar in the center. The piers sit 5-feet deep in clay soil and protrude from one to six inches above ground depending on the slope of the terrain.

Fig. 7. (Right) Pier spacing.

The support frames are fastened to the footings via half-inch anchor bolts and metal plates (Fig. 8) that permit vertical adjustment of the frames. The mounting angle of the array support structure was drilled on 8-foot centers to permit attachment of frames.

The galvanized frame hardware was dipped in a 5-percent hydrochloric solution, and the 20 support structures were assembled. The support frames were then sprayed with a zinc-chromate primer coat followed by two coats of white epoxy paint.

Fig. 8. Pier array mounting bracket.

2.2 Field Wiring

2.2.1 Array

Standard 3-3/4-inch bell boxes are mounted to each array frame. Flexible, waterproof conduit interconnect the boxes between adjoining frames and the rigid, 3/4-inch conduit system to permit individual adjustment of each support frame (Fig. 9). The wires from the subfield unit enter the conduit through rubber grommets fitted with openings drilled in the bell boxes.

The support structure for each row is grounded at the center and at both ends by 6-foot-long copper ground rods with grounding straps.

Prior to installing the modules on the support frames with 1/4-inch bolts, an 1N5404 diode was attached across each module's positive and negative terminals for electrical protection.

The array was wired with No. 14 AWG stranded copper wire and all wire connections to the array and field junction box were crimped. All wires going to the field junction box were labeled and each terminal cover on the module was marked with the subfield unit number.

2.2.2 Field Junction Box

Refer to Fig. 10. Red and black test jacks wired to each subfield unit switch permit testing of subfield units where they can be short circuited, open circuited or routed to the PV main control box. Three measurements can be made: operating voltage, open-circuit voltage, and short-circuit current. The open-circuit voltage is measured across the subfield unit test points with a DC voltmeter with the field junction box switch, S1, in the open-circuit position. The short-circuit current is measured by connecting the current shunt provided in the field junction box. A multi-meter with a millivolt range is connected across the shunt. switch is then placed in the open-circuit position, which results

NORTH

Fig. 9. Field Conduit Diagram.

in the shunt being connected electrically across the subfield unit's output. The conversion factor is 50 mVDC equals 3 ADC. The operating voltage of the main bus voltage is measured across the test points with a DC voltmeter with the switch in the ON LINE position (provided that the proper relay closure is made in the main control box).

Fig. 10. Field Junction Box Wiring.

2.3 PV Main Control Panel

The PV main control panel, located in the SERF garage, provides two primary functions:

- a. It opens, closes, and connects each of the 24 subfield units to the DC bus.
- b. It monitors each subfield unit manually by front panel meters, or by the computer control/data system (Fig. 11).

When relay K1 is closed each subfield unit is connected to the DC bus and when relay K2 is closed, each subfield unit is short circuited. These relays may be opened and closed by the computer when the 3-position front panel switches, S3 and S4, are in the AUTO position (Fig. 11). Front panel indicators L1 and L2 light when relays K1 and K2 are closed. When switch S3 is placed to OPEN CIRCUIT and switch S4 is placed in OFF, relays K1 and K2 are opened. When switch S3 is placed to ON LINE and switch S4 is placed to SHORT CIRCUIT, relays K1 and K2 are closed. Diode D1 prevents shorting of the DC bus should relays K1 and K2 be closed simultaneously. Each subfield unit is protected with 3-Amp fuses (F1) before being connected to the bus. The DC bus is not fused in the main control panel since the inverter is provided with 45-Amp fuses on the DC input.

To monitor each subfield unit, select the desired subfield unit with the front panel rotary switch S2. With switch S3 in the ON LINE position and switch S4 in the OFF position, front panel meters M2 and M3 will indicate the subfield unit's operating voltage and operating current. With switch S3 in the OPEN CIRCUIT position and switch S4 in the OFF position, meter M2 will indicate the open-circuit voltage and meter M3 will indicate zero. When switch S3 is in the OPEN CIRCUIT position, meter M3 will indicate the short-circuit current and meter M2 will indicate zero. The total DC bus current is displayed continuously on meter M1.

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Fig. 11. Main control box wiring.

2.4 High Voltage DC/AC Wiring and Metering

Refer to Figs. 12 and 13.

Each of the power meters contains pulse initiators that provide a pulse to the data system for each rotation of the meter disk. These pulses are counted by the pulse counting board in the computer. The pulse counting board is read, recorded on the data disk, and reset each time the system is scanned.

Fig. 12. PV High-Voltage DC/AC Wiring and Metering.

C00-4517-5-12

Fig. 13. SERF Meter Diagram.

3.0 SOLAR THERMAL SUBSYSTEM

A flat-plate, liquid-solar-collector subsystem is used together with the PV subsystem to evaluate direct solar heating and solar-assisted heat-pump heating of the SERF residence. The flat-plate subsystem consists of the following components: 22 Northrup FP1G flat-plate collectors; liquid thermal storage; two-speed, 3-ton-capacity, Lennox Industries heat pump; a fan/coil duct-delivery system.

The collectors cover an area of 520 square feet and are mounted on support structures similar to the PV support frame. Thermal storage is provided by three water storage tanks operated at low (for cooling), medium, and high temperatures. The well-insulated tanks are located in the SERF garage.

Direct solar heating is achieved by circulating hot water from the storage tank through the heating coil in the air-handling unit (Fig. 14). The solar-assisted heat-pump heating operates

Fig. 14. Direct Heating Collection and Storage System.

when the temperature of the storage tank is less than the cutoff temperature for solar-assisted heat-pump heating. During solar-assisted heat-pump operation, water is circulated from storage through the heat-pump evaporator and returned to storage (Fig. 15). Heat is rejected by means of heat-pump condenser water that is pumped to the heating coils in the air-handling units.

Fig. 15. Heat-pump heating system.

3.1 Water-to-Water Heat Pump

The heat pump, using a two-speed, compressor-driven, Freon loop and water-to-water evaporator and condenser, was designed and built during 1975 as an experimental unit. The two-speed compressor design was unique.

Data included on the nameplate:

Model No.	L7-04522A-A1
Serial No.	5120197
Motor (Century):	Single phase, 60 Hz, 230 V
Compressor:	1-7/8 in. bore
	0.920-in. stroke
	2.54 cu. m. displacement
	3450 rpm high speed
	1725 rpm low speed
	613.90 cu. ft/hr (high)
	306.95 cu. ft/hr (low)
Speed change:	High→low at 42 psig or 36°F evaporator
	Low→high at 48 psig or 42°F evaporator
Refrigerant:	Freon, R-500
Capacity (nominal):	3-ton (4 ton with Freon, R-22)

The cooling capacity calculated at high speed is shown on Fig. 16.

Fig. 16. Calculated cooling capacity of heat pump model L7-04522A-A1 at high speed.

The cooling capacity calculated at low speed is shown on Fig.

Fig. 17. Calculated cooling capacity of heat pump model L7-04522A-A1 at low speed.

The cooling coefficient of performance is shown on Fig. 18.

* GPM = $C/498.89$

Fig. 18. High-speed (3450 rpm) performance test data for two-speed heat pump.

The pumping flow rate as a function of evaporator temperature is shown on Fig. 19.

Fig. 19. Calculated pumping rate of heat pump model L7-04522A-A1: high speed, 3450 rpm; low speed, 1725 rpm.

3.2 Air Handler

A two-speed, Lennox Industries, fan/coil unit containing four electric strip heaters and a 5-ton-capacity, 4-row water coil for house heating and cooling was built especially for the SERF project. For heating, the unit receives water either from high-temperature storage or from the heat pump. For cooling, chilled water is received either directly from the heat pump or from the chilled water storage. The speed of the fan is changed by changing the placement of the belt on the pulley sheaves.

Data included on the nameplate:

Part No.:	8-108185-02
Frame No.:	L.56
Motor (Century):	
Type:	CSM 3/4 hp, 60 cycle, single phase
High speed:	1725 rpm, 5.0 A
Low speed:	1140 rpm, 2.0 A
Motor pulley:	4-inch diameter
Fan pulley:	8-inch diameter
Heat exchanger:	32-inch-long, 1/2-inch-diameter copper tubing 36 tubes (4 tubes, 9 passes each)

3.3 Cooling Tower

The Halstead-Mitchell cooling tower is a 7-1/2-ton-capacity, horizontal, induced-draft tower with a solid-state-controlled modulating fan.

Data included on the nameplate:

Model No.:	GCKA-7.5
Serial No.:	7.5-3811
Motor (Century):	
Part No.:	7-130648-02
Frame No.:	GM482
Type:	CX, 1/3 hp, 230 V, 60 Hz, single phase, 1090 rpm, 2.2 A Direct drive to fan

3.4 Flat-Plate Collector Array

Twenty-two Northrup, Inc., FP1G, flat-plate, liquid collectors have been installed for direct solar heating and as a heat source for the heat pump. The collector array is connected to thermal storage by approximately 50 feet of 1-1/2-inch ID copper tubing that is insulated by 1-1/2-inch-thick urethane foam.

3.5 Thermal Storage

Thermal storage is provided by three tanks as described below:

- 1843-gallon, steel, chilled water storage tank
- 1043-gallon, steel, hot water storage tank
- 1200-gallon, concrete, medium-temperature storage tank.

The 115-inch-long by 71-inch-diameter chilled water tank with torispherical end caps is used in conjunction with the heat pump for off-peak cooling. A minimum of 6-inch-thick sprayed-on polyurethane foam provides a theoretical thermal resistance of R-36. Specifications for the steel tanks are given in Table 1.

TABLE 1
STORAGE TANK SPECIFICATIONS

Capacity	1250 gallons minimum
Overall dimensions	Maximum length: 10 ft Maximum diameter: 5 ft Maximum height: 6 ft 4 in.
Pressure	Operating: 50 psig maximum Proof: 75 psig maximum (no permanent deformation or leakage)
Temperature	260°F maximum 10°F minimum
Fluid	Water
Material	Steel
External leakage	Insufficient to form a drop at 260°F, 50 psig in 8 hours
Insulation	Thermal resistance factor of R-33 or 4-inch-thick, closed-cell polyurethane foam or equivalent
Corrosion protection	Internal lining to prevent rust in water service
Supports	As required to prevent tank movement and protect insulation
Fittings	Nine (including drain) 2-inch-diameter, threaded, galvanized steel pipe nipples
Inspection port	Approximately 16-inch-diameter, bolted-flange cover with seal

The hot water storage tank, used for direct solar heating (connected to the concentrating collector array) and as a source for heat-pump heating, has torispherical end caps. It is insulated with 6-inch-thick fiber glass bats (including two foil radi-

ation barriers), approximately four inches of loose Vermiculite masonry insulation, and a 4-1/2-inch-thick (R-16) enclosure of Tectum II.

The rectangular, medium-temperature, steel-reinforced, concrete tank with inside dimensions of 46 x 61 x 112 inches is used for direct solar heating (connected to the flat-plate collector array) and as a source for heat-pump heating. The heat exchanger's copper tubing coils inside the tank connect to the collector array and heat pump. This unpressurized tank is insulated by a 3-inch-thick coat of polyurethane foam (R-18).

4.0 SYSTEM COST

The cost of equipment and installation of the PV solar thermal system is shown in Table 2. It reflects UTA and/or MIT/Lincoln Laboratory cost figures. Labor was provided by students and technicians primarily at an average cost of five dollars per manhour.

TABLE 2
SYSTEM COST

Component	Material Cost (\$)	Labor to Install (manhours)
Inverter, 8 kW	2,225 (1977) ⁺	120
Isolation transformer (15-kW pk)	370 (1978)	
Structure (PV)		
Frames*	5,490 (1978)	220
Fasteners	655 (1978)	
Photovoltaic modules	131,670 (1977)	120
\$16.50/W, 7980 W at 100 mW- cm ⁻² and 28°C		
Flat-Plate (thermal) collectors (22 panels, 520 sq ft)	5,270 (1978)	40
Structure (thermal) ⁺	1,018	180
Footings (including site preparation)		
Thermal	290 (1978)	120
Photovoltaic	720 (1978)	300
Wiring (PV)		
Panels	1,225 (1978)	400
Controls	1,921 (1978)	300
Plumbing (thermal)	1,600 (1978)	120
Tank (concrete)	882 (1978)	80

* Total frame area: 1200 square feet.

⁺ Flat-Plate frame area: 600 square feet.

⁺ Year purchased.