Solar Photovoltaic Air Conditioning of Residential Buildings

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The use of photovoltaics (PV) for residential air conditioning (AC) represents an attractive application due to the close match between the diurnal cooling load and the availability of solar radiation. Conventional wisdom suggests that air conditioning is a process too energy intensive to be addressed by PV. Previous investigations have concentrated on the feasibility of matching PV output to vapor-compression machines, and the cost effectiveness of other solar cooling options. Recently, Japanese manufacturers have introduced small (8,000 Btu/hr) grid-connected solar assisted AC systems. These small room-sized systems are inadequately sized to meet air conditioning peak demands in larger U.S. homes of conventional construction practice. Previous studies considering the use of PV for solar cooling have treated the building thermal load as a fixed quantity. However, the large initial cost of PV systems ($6-$10/W_{peak}) makes minimization of the building loads highly desirable. This paper describes a novel approach whereby the building, air conditioning and PV systems are simultaneously optimized to provide maximum solar cooling fraction for a minimum array size.

A detailed hourly building energy simulation in a hot-humid climate is used to assess methods of reducing the building sensible and latent cooling loads to a practical minimum. A detailed PV system simulation is used to determine the match of the array output to that of the building's peak loads. The paper addresses several key elements that influence the concept's feasibility and potential economic attractiveness.

Introduction

The few prior studies of PV-powered AC have concentrated on the feasibility y of matching PV output to vapor-compression machines, and the cost-effectiveness of competing options [Kern 1979; Stephens et al., 1980]. Recently, three Japanese manufacturers have announced commercialization and test results for small (8500 Btu/hr) grid-connected PV assisted AC systems Tanaka et al., 1990; Sawai 1992; Takeoka et al., 1993]. In the United States, the Electric Power Research Institute is testing PV-powered heat pumps [EPRI 1993].

All previous investigations considering the use of PV for solar cooling of buildings have treated the building thermal load as a fixed quantity. However, the large initial cost of PV systems ($6-10/$W_{peak}$) makes minimizing the building load highly desirable. A number of conservation measures can decrease the load at a lower cost than the load can be satisfied with PV. Substantial reductions are therefore possible in the required PV system and AC unit size, and the thermal delivery system. One limitation, however, is that the approach would be practical only for new home construction. Initially, three fundamental cases were defined to characterize residential electrical load profiles:

1. *Base Residential Building:* This case represents current building construction practice and employs standard efficiency electrical appliances and HVAC equipment.

2. *Minimum Cooling Energy Residential Building:* This case represents an all-electric residence with thermally optimized construction and incorporates all available methods to reduce building cooling and electrical loads.

3. *Minimum Electricity Residential Building:* This case is identical to case 2 except that natural gas is used instead of electricity for appropriate end-use appliances.

Base Residential Building

A prototype building, typical of residences in southern climates, was used to define characteristics for the base residential building [Fairey et al., 1986]. Table 1 summarizes the assumptions.

Three occupants were assumed in the prototype residence with typical electrical appliances. The specific end-use

Table 1. Building System Specifications Base Residential Building

Primary Characteristics		
Location:	Central Florida	
Type:	Single-story, long axis faces north-south	
Floor Area:	1,500 ft^2 (139.4 m^2); slab-on-grade	
Roof:	Asphalt shingles, plywood decking: 20° roof slope	
Ceiling Insulation:	RSI 3.35 (R-19) over 1.3 cm sheetrock	
Wall Construction:	Concrete block; RSI-0.88 (R-5) interior insulation	
Windows:	214 ft^2 (19.9 m^2); single glazed w/aluminum frame	
Heating and Cooling		
Heating:	3-ton heat pump, COP = 2.3	
Cooling:	3-ton heat pump, SEER = 10.0; SHR = 0.8	
Distribution:	Attic ducts; RSI-0.88 (R-5) rigid fiberglass insulation	
Appliances		
Elec. Water Heater:	Storage type, 200 liter, 3271 kWh/yr	
Standard Refrigerator:	Std. efficiency, 17 ft^3 (480 l), 1,460 kWh/yr	
Lighting:	Incandescent, 1095 kWh/yr	
Clothes Dryer:	Electric	
Operation		
Heating T-stat:	22.2°C (72°F)	Internal Heat Gains: Average 648 W
Cooling T-stat:	25.6°C (78°F)	Cooling Season: April-October

electrical demand profiles were taken from sub-metered appliance load data gathered from a large sample of homes during the summer months [Pratt et al., 1989]. The hot water electrical demand profile was based on measured data collected on 18 electric resistance water heaters in Florida [Merrigan 1983].

Minimum Cooling Energy Residential Building

Energy efficient improvements to the building envelope result in significant AC load reductions. These improvements include wall and ceiling insulation, white exterior walls, a reflective roof, reflective windows, landscape shading of walls and windows, and a ductless AC system [Fairey et al., 1986; Parker 1990; Parker et al., 1992; Parker et al., 1993]. Internal heat gains represent the largest component of the AC load in typical, well-insulated residential buildings. Accordingly, the minimum cooling energy building features a variety of proven technologies to reduce the internal load from appliances and lighting. Table 2 summarizes the methods (and their cost) used to reduce the base residential building AC load to the minimum cooling energy building AC load.

The AC load conservation measures presented above behave according to a law of diminishing returns: decreased savings are realized from each additional measure implemented. Figure 1 shows how the minimum cooling energy building was optimized by adding the most effective options in order of their incremental contribution to reducing the peak day cooling load (optimization by steepest descent).

Minimum Electricity Residential Building

Methods were also examined to reduce the overall building electrical loads to a practical minimum. This was accomplished by substituting non-electric fuels in place of electrical appliances where applicable. For the minimum

Table 2. Thermal Efficiency Improvements: Methods and Cost Minimum Cooling Energy Building

Min. Cooling Energy Residential Building	Base Residential Building	Justification
Roof/Ceiling ($535)		
RSI-5.3 insulation	RSI-3.3 insulation	Reduces heat conduction
Reflective Roof or RBS	None	Reduces heat transfer
Concrete Block walls ($1,065)		
RSI-1.9 on exterior	RSI-0.9 on interior	Reduces conduction/shifts peak
White exterior	Medium color	Reduce solar absorptance
Landscape shading	None	Reduces solar absorptance
Windows ($1,560)		
Reduce E/W windows	Equal Distribution	Reduces summer solar gains
Double-glazed	Single-glazed	Reduces conduction
Reflective	No coating	Reduces solar transmission
Low-ϵ coating	No coating	Reduces radiant transfer
Awning type	Double-hung	Increase ventilation potential
Landscape shading	None	Reduces solar transmission
Internal Loads and Appliances ($555)		
Hi-Eff. Refrigerator	Standard	Reduces associated gains: 70%
Hi-Eff. Fluor. lights	Standard incandescent	Reduces gains by 70%
Motion Sensors	None	Controls ceiling fans/lighting
Lo-Flow Shower/WH insul	Standard tank	Reduces DHW loads
WH located outside AC	located inside	Reduces gains from tank
Mechanical Air Conditioning System ($1,375)		
EER of 12 or better	EER = 10	Reduces AC energy use
Sized to meet load	Oversized by 1-2 tons	Reduces AC power demand
Ductless AC system	Located in attic	Reduces AC loads 20-30%
Shade AC condenser	Unshaded	Improves AC EER by 2-5%
Total Costs = $5,090		

Source of cost data: Parker et al., 1992, p. 28.

electric residential profile described here, solar for water heating with natural gas backup and natural gas for cooking, heating and clothes drying are used instead of electricity. In an all-electric residence, these appliances result in peak load demands over short periods. By substituting gas or alternative fuels, the peak load can be satisfied by a smaller PV system than would be required for the all-electric residence.

Building System Analysis

For the three residential cases presented above, an hourly building energy simulation program, *FSEC 2.1,* was used to compute hourly electrical demand profiles for both the AC and appliance loads [Kerestecioglu et al., 1989]. The building load simulation, as well as the subsequent PV system modelling were performed using Typical

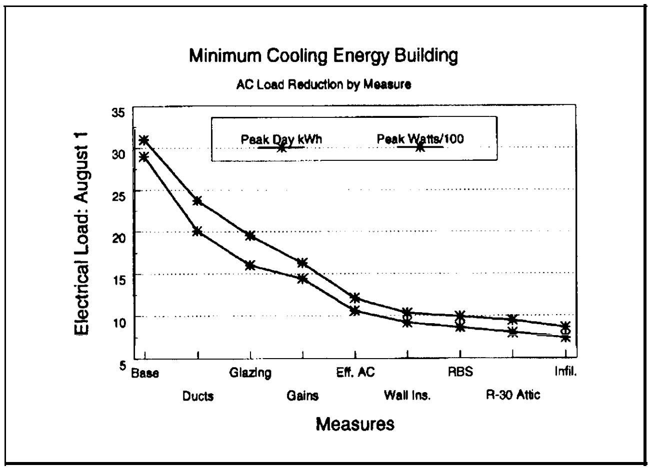

Figure 1. Energy Conservation Measures for Minimum Cooling Energy Building

Meteorological Year (TMY) data for Orlando, Florida [TMY User's Manual 1981]. The cooling-dominated Central Florida climate was used since it induces in an extreme AC load. In addition, the variability of summer afternoon insolation suggests examining the match between peak residential AC loads and PV system performance.

Figure 2 summarizes key climatic data for the year; Figure 3 presents the hourly average temperature, insolation, relative humidity and wind speed for the summer peak cooling load day of August 1st.

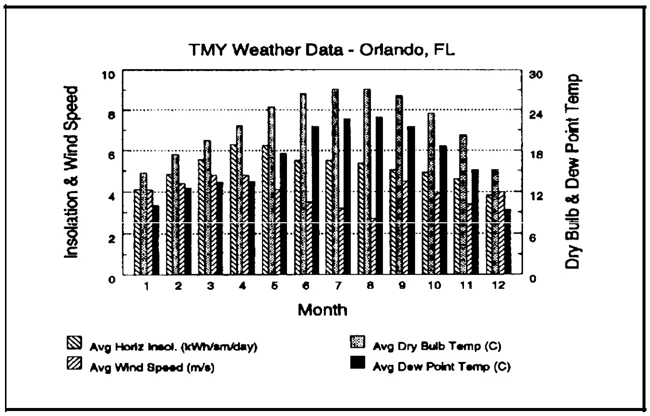

Figure 2. Annual Weather Data for Orlando, FL

Table 3 summarizes the annual results of the *FSEC 2.1* simulations for the three residential building load cases. Predictions for the base case (11,312 kWh/yr) were consistent with the mean energy consumption of 177 all-electric homes in Florida (12,900 kWh/yr) as measured in the field [Vieira and Parker 1991]. The predicted AC loads were reduced from 2,968 kWh for the base case to only 681 kWh for the minimum cooling energy building. High-efficiency lighting, refrigeration and hot water conservation measures resulted in a reduction of appliance electricity use of 2,991 kWh for a total annual electrical savings of 5,277 kWh. At an energy cost of $0.07/kWh, these measures offer an annual savings of $369 with a simple payback of about 14 years.

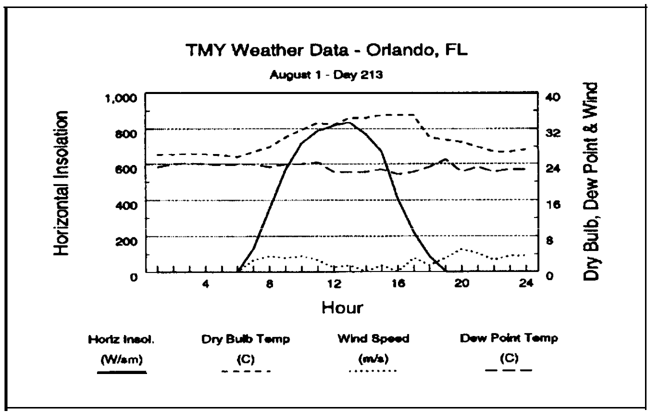

Figure 3. Weather Data for August lst, Orlando, FL

Most notably, the annual energy use for the minimum electricity residence was only 2,091 kWh-a decrease of 82% compared to the base case. These measures are able to offset an estimated 3,859 kWh per year electrical demand (550 to 900 W peak) at an incremental cost of only $150. The electric savings are achieved with the additional use of approximately 190 therms/yr of natural gas.

On the peak load day of August 1st, the AC energy consumption was reduced from 31 kWh for the base case to below 8 kWh for the minimum cooling energy building. The coincident peak AC load on the same day was reduced by over 2 kW.

The base case building had a maximum cooling load on August 1st of 8,292 W (28,300 Btu per hour) as compared to 2,461 W (8,400 Btu/hour) for the minimum cooling energy building. Clearly, the newly available small Japanese AC units would be unable to adequately cool the base case house but could theoretically provide the necessary cooling for the minimum cooling energy building.

PV System Analysis

Several strategies are conceivable for integrating PV in residential buildings to satisfy all or part of the loads. In a stand-alone configuration, the PV system would be designed independent of the utility grid to interface directly with the load or with battery storage. The loads would be operated with dc power, or with ac power with the use of a stand-alone inverter connected to the battery. In a grid-connected or utility-interactive configuration, a power conditioner is used to interface the PV array output with the utility. The building load and PV array output then dictate the direction of energy flow between the PV, load and utility.

Table 3. Summary of Building Electrical Loads

Residential Building Type	Annual Heating (kWh)	Annual Cooling (kWh)	Annual Appliance (kWh)	Annual Total (kWh)
Base	94	2,968	8,344	11,312
Min. Cooling Energy	8	681	5,260	5,950
Min. Electricity(a)	0	681	1,408	2,091

(a) Natural Gas consumption not included for minimum electricity building, but comprises approximately 190 therms/yr.

Both the stand-alone and grid-connected configurations have been successfully employed for residential power. Often, the PV array for grid-connected residential systems is deliberately undersized to provide only peak load reduction and is not sized to meet the entire load. The reasoning for undersizing the PV array is due to the low value for energy sold to the utility as compared to the high cost of PV generated energy.

For the analyses presented here, only grid-connected systems are considered. Although not presented here, PV AC systems without the ability to either serve other non-cooling loads or to sell-back electricity to the utility appear impractical.

PV system characteristics typical of residential installations were used for the analysis. It was assumed that the array was located on a south-facing, 200 roof slope. Furthermore, efficiencies typical of current PV systems technology were used, including an array efficiency of 10% and a power conditioner (inverter) efficiency of 90%.

The ability of PV systems to contribute capacity during the peak electrical demand periods is of significant interest to electric utilities [Russell and Kern 1992]. Our analysis seeks to define PV array sizes, electrical storage requirements and utility rate structures that offer the best near-term market for residential PV systems.

Preliminary Sizing Estimates

To attain a first approximation of the PV system sizes required to meet the daily energy and 5-6 p.m. peak loads on the maximum cooling load day of August 1st, the following equation was used:

$$A = \frac{L}{I \eta_a \eta_s t}$$

where A = array size (m^2)
L = design load (Wh)
I = avg insolation for period (W/m^2)
$_a$ = array efficiency
$_s$ = storage/power conditioner efficiency
t = period of the insolation cycle (hrs)

For the daily load, the insolation value of 6.35 kWh/m^2 for August 1st on a south facing, 20° tilted surface was used to calculate the array size. For the 5-6 p.m. peak summer load period defined by Florida utilities, a value of 208 W/m^2 was used to determine the required array size to meet the peak.

The daily and peak loads for August 1st, along with the required PV array area to meet the daily energy and peak load are summarized in Table 4.

The results show that a very large reduction in array size is possible through the use of building improvements to reduce cooling loads. A considerably larger PV array is needed to offset the 5-6 p.m. utility peak without storage or utility backup. The array sizes required to meet the entire base building loads are clearly impractical since the required collection area may exceed that of an entire residential roof.

PV System Hourly Simulation

An obvious limitation of the above analysis is that it does not examine how well the PV system output matches the coincident building load over the entire year. To analyze the performance of different PV array sizes with the three residential load profiles, the computer program *PVFORM* was used to determine the hourly contributions of the PV array and utility (backup) in meeting the load [Menicucci and Fernandez 1988]. Table 5 summarizes key input parameters were used in the PVFORM simulations.

Table 4. Electrical Loads and Predicted Array Sizes, August 1 - Day 213

Case Description	Daily Load: kWh (Array Size m^2)	5-6 pm Peak Load: W (Array Size m^2)
Base Case Building		
AC Only	28.8 (50)	2,680 (143)
All electrical loads	48.8 (85)	3,470 (185)
Minimum Cooling Energy Building		
AC Only	7.2 (12)	642 (34)
All electrical loads	19.6 (34)	1180 (63)
Minimum Electricity Building		
AC Only	same as min. cooling energy building	
All electrical loads	10.8 (19)	779 (42)

Table 5. PVFORM Input Parameters

365 day load profile
TMY data Orlando, FL
Site latitude 28.5°
Array tilt 20°
Array azimuth 0°
Array area 5, 10, 20, 30 and 40 m^2
Mismatch and line losses 3.5%
Ground albedo 0.3
Installed NOCT 46°C
Reference temperature 25°C
Reference efficiency 10%
Efficiency red. coeff. 0.43%/°C
PCU input 0.5, 1, 2, 3 and 4 kW
PCU efficiency 90%

Utility Rate Calculations

Software was written to read the *PVFORM* hourly output files and to analyze the effects of different utility rates, energy storage and PV array sizes on the value of the energy bought from and sold to the utility. The cost of electricity sold to and bought from the utility were developed based on discussions with major electric utilities in Florida. While the rates are not specific to a particular utility, the rates are typical of what would be available to a residential PV system owner. Three utility rates were defined for our analysis:

1. *Co-Generation Rate (Co-Gen)*

Energy Bought From Utility ($/kWh)	$0.070
Energy Sold To Utility ($/kWh)	$0.030

2. *Time-of-Use Rate (TOU)*

Winter Peak Time: Nov.-Mar. 6am-10am & 6pm-10pm.
Summer Peak Time: Apr.-Oct. 12pm-9pm.
All other times off-peak.

Energy Bought From Utility (On Peak, $/kWh)	$0.079
Energy Bought From Utility (Off Peak, $/kWh)	$0.027
Energy Sold To Utility (On Peak, $/kWh)	$0.040
Energy Sold To Utility (Off Peak, $/kWh)	$0.030

Analysis Results

Annual results for selected cases are presented as a series of tables. Table 6 examines the performance of a 1 kWp PV array as affected by the specific building use analyzed. Table 7 illustrates the influence of array size on annual performance for the base building (AC load only). Table 8 compares the performance of a 1 kW$_p$PV system with the Co-Gen rate and time-of-use rate (TOU) for both the AC and all electrical loads.

Examination of these results leads to several conclusions:

- Building efficiency has a profound effect on the ability of a PV array to serve the AC load.

Table 6. Sensitivity of Annual Performance to Building Type (1 kW_p PV, Co-Gem Rate)

	kWh				$		
Building Type	**PV to Load**	**PV to Util**	**From Util**	**Load**	**Sell to Util**	**Buy from Util**	**Load w/out PV**
Base-AC	1516	695	2146	2968	$21	$150	$208
Base-All	1516	0	9795	11312	$0	$686	$792
Min Cool-AC	1516	1035	201	681	$31	$14	$47
Min Cool-All	1516	20	4453	5949	$1	$312	$416
Min Electric	1516	618	1192	2091	$19	$83	$146

Table 7. Sensitivity of Annual Performance to PV Array Size (Base Building: AC only, Co-Gen Rate)

	kWh				$		
Array Size	**PV to Load**	**PV to Util**	**From Util**	**Load**	**Sell to Util**	**Buy from Util**	**Load w/out PV**
0.5 kW_p: 5 m^2	758	334	2544	2968	$10	$178	$208
1 kW_p: 10 m^2	1516	695	2146	2968	$21	$150	$208
2 kW_p: 20 m^2	3032	1547	1482	2968	$46	$103	$208
3 kW_p: 30 m^2	4548	2672	1092	2968	$80	$76	$208
4 kW_p: 40 m^2	6066	4018	922	2968	$121	$65	$208

Table 8. Effect of Time-of-Use Rate on Annual Performance (1 kW_p PV)

	kWh				$		
Configuration Type	**PV to Load**	**PV to Util**	**From Util**	**Load**	**Sell to Util**	**Buy from Util**	**Load w/out PV**
Base-AC	1516	695	2146	2968	$21	$150	$208
Base-AC/TOU	1516	695	2146	2968	$22	$138	$208
Min Cool-AC/TOU	1516	1035	201	681	$31	$14	$48
Min Cool-AC/TOU	1516	1035	201	681	$34	$13	$48
Base-All	1516	0	9795	11312	$0	$686	$792
Base-All/TOU	1516	0	9795	11312	$0	$457	$792
Min Electric	1516	618	1192	2091	$19	$83	$146
Min Elec/TOU	1516	618	1192	2091	$20	$52	$146

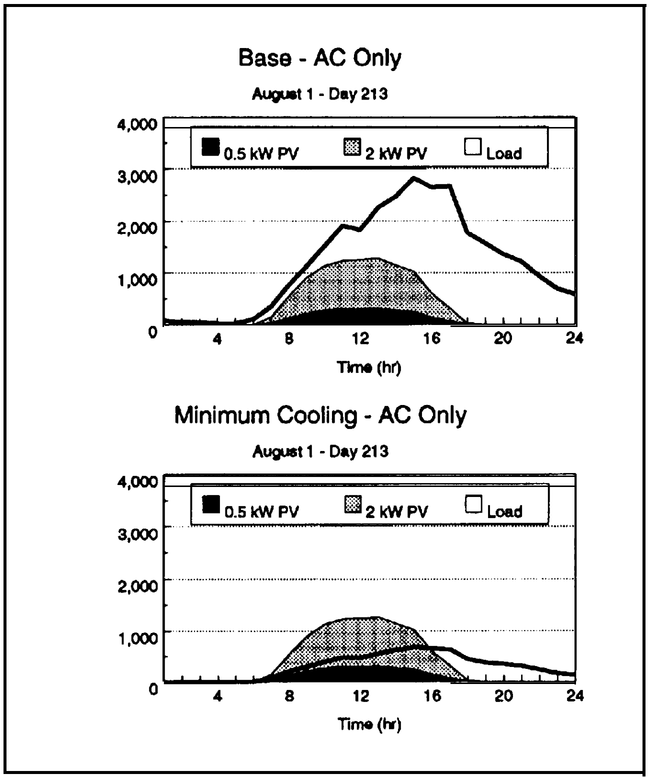

Figure 4. Air Conditioning Load and PV Output for Base and Minimum Cooling Energy Building, August 1st

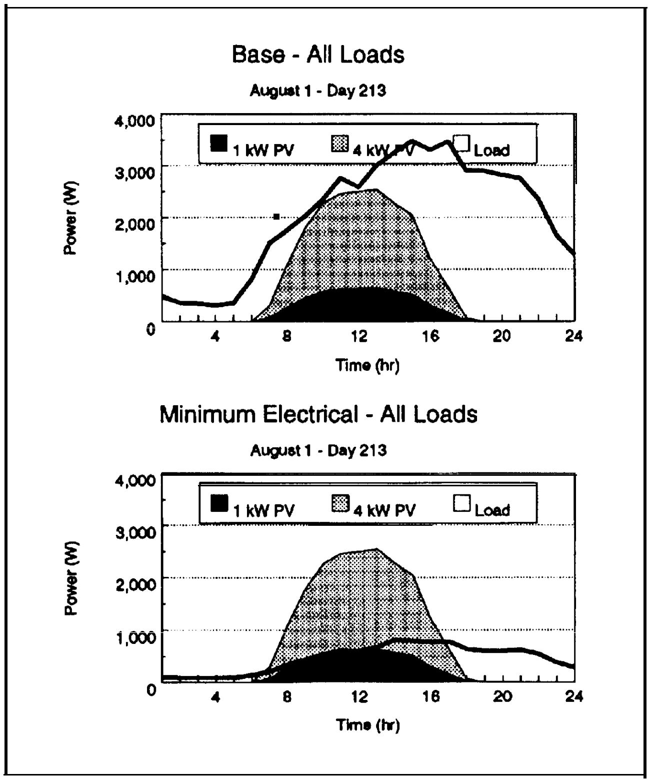

Figure 5. All Electrical Loads and PV Output for Base and Minimum Electrical Energy Building, August 1st

- Improvements to building efficiency are currently more cost-effective than increasing PV array size for reducing electrical loads.

- Time-of-use (TOU) electrical rates appear to be advantageous for PV grid-connected applications.

Figure 4 shows the August 1st AC load and the PV system performance (0.5 and 2 kW$_p$ arrays) for the base and minimum cooling energy buildings. Figure 5 presents the PV system performance (1 and 2 kW$_p$ arrays) for all loads for the base and minimum electrical building cases.

Key findings from the examination of the load shape profiles (Figures 4 and 5) for the peak cooling load day of August 1st include:

- The AC and overall building peak cooling load occurs approximately 4 hours after the peak PV system output .

- The AC load for the base building requires an array size of approximately 4 kW to meet the majority of the peak load.

- The majority of the AC load for the minimum cooling energy building can be met with a 1 kW$_p$ PV array. Also, the cooling load appears to closely match the output of the PV system on the peak day.

- The electrical load of the minimum electricity residential building is best matched by a 1 kW array.

Conclusions

A fundamental objective of this study was to examine considerations for using PV to satisfy residential AC loads. Perhaps the most significant conclusion was that the required PV system size can be greatly reduced by minimizing the building cooling load. Improvements to the building envelope and appliances were able to decrease the cooling load by over 75%, reducing the required PV array size by a factor of four. At a cost of approximately $5,100 for the improvements, this achieves a load reduction more cost-effectively than by sizing the PV array to meet the base case load. Given the seasonal nature of the cooling load, it is apparent that a residential PV system be able to displace other electrical loads during the non-summer months. A PV system that served all building loads saved nearly twice as much in annual utility costs than a system which powered the AC system only. In most cases, TOU utility rates will be beneficial when used with residential PV systems.

In our analysis, both the building and PV system simulations were driven by hourly weather data. However, actual building electrical loads exhibit short-term "needle" peaks which can exceed the hourly average load profile. This problem is greatest for buildings with all-electric appliances; therefore the analysis presented here for the base case building must be considered somewhat optimistic.

Future analysis of PV AC systems should also consider how array axis-tracking, load shifting, thermal or electrical storage and intelligent building systems influence the ability of a PV system to meet the coincident peak loads. One potentially attractive option would be to use the PV AC system to pre-cool an exterior insulated masonry building in the non-peak morning hours. Another option to the matching of PV array output with AC loads is to use a non-south azimuth to delay the timing of maximum array output. For instance, based on a combination of empirical data and simulation, Nawata (1992) showed that the optimal orientation of a solar cooling system in Japan consisted of an optimal azimuth approximately 20 degrees west of due south with an array slope of latitude minus ten degrees. However, regardless of approach, a comprehensive optimization of solar cooling systems suggests the use of analytical methods which account for potential tradeoffs between building thermal efficiency, array area, thermal storage capacity and other relevant parameters [Fukushima et al., 1992].

A key question, not addressed by this preliminary study, is the cost-effectiveness and practicality of the options considered. This may be appropriate after further study has identified the most desirable system configurations (building efficiency, PV size, thermal or electrical energy storage and operational strategies). The life-cycle costs of the various options and hardware compatibilities should then be examined. Finally, a full-scale demonstration of potentially competitive configurations should be undertaken in residential buildings to verify predicted results.

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