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Energy Savings Estimates and Cost Benefit Calculations for High Performance Relocatable Classrooms

FINAL REPORT

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HPCBS Element 6, Project 2.1.2: Energy Savings Estimates and Cost Benefit Calculations for High Performance Relocatable Classrooms

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Executive Summary

Program Element 6 of The High Performance Commercial Building Systems (HPCBS) project involves both modeling and monitoring of the performance and cost-effectiveness of high performance relocatable classrooms (RCs). During typical years roughly 4,000 RCs are installed in California, although recent class size reduction efforts have increased annual production to close to 10,000 units. Cost-effective improvements in RC energy efficiency provide cost savings while improvements in indoor air and environmental quality (IEQ) have the potential to create a healthier and more productive learning environment for K-12 students in California.

A high performance RC "package" featuring improved envelope components, high efficiency lighting, and an advanced hybrid HVAC system was installed in four RCs. Conventional 6.8 HSPF/10 SEER wall-mount heat pumps (HPAC) were installed in parallel with the advanced hybrid systems to allow system switching on a weekly basis, allowing each classroom to act as its own control. The advanced hybrid system features a variable speed two-stage indirect-direct evaporative cooler (IDEC) combined with an instantaneous gas water heater and pump which supplies hot water to a hydronic coil. The advanced hybrid system also provides minimum outdoor air ventilation (15 cfm/person) during occupied hours. Although continuous ventilation is beneficial from an indoor air quality perspective, the higher ventilation rate increases space conditioning loads. The challenge of this project is to demonstrate IEQ improvements can be achieved while saving energy.

Two RCs with dual HVAC systems each were installed at schools in Modesto and Cupertino, California, and monitored from September 2001 to June 2002. Detailed data on energy use, air temperatures, relative humidities, and system operation were collected on six-minute intervals. Data for occupied days were analyzed and regression relationships were developed to characterize daily electrical and gas consumption as a function of average daily outdoor temperature. A DOE2 building simulation model was validated using the monitoring from the two RCs at each site. Base case HVAC performance was found to be considerably poorer than the expected nominal HSPF and SEER for the wall-mount HPAC's. Full season heating and cooling performance was approximately 30% below the nominal HPAC seasonal values, primarily due to thermostat control issues and typically short run cycles.

The validated model was used to generate performance projections in all 16 California climate zones for both advanced hybrid systems and high efficiency HPACs (6.8 HSPF, 12 SEER). Continuous minimum outdoor air (21 occupants with 15 cfm/person) was modeled in both cases to ensure consistency between the simulated loads. Operating costs were tabulated based on statewide average blended commercial rates of $0.147 per kWh and natural gas rates of $0.74 per therm. Based on the assumed statewide distribution of RCs, the following "per unit" weighted average impacts were determined:

- 1,494 kWh saved (82% reduction)
- 5.9 kW winter peak electric load reduction (96% reduction)
- 3.3 kW summer peak electric load reduction (72% reduction)

- 26 therm gas increase
- 13 Mbtu source energy savings (69% reduction)
- $220 annual operating cost savings, ranging from $159 to $385 (82% reduction)

The statewide technical potential based on converting 4,000 new RCs to advanced hybrid systems is projected to:

- save 5,975 MWh of electricity per year
- reduce winter peak electric load by 23.8 MW
- reduce summer peak electric load by 13.1 MW
- increase natural gas consumption by 1025 Mbtu per year
- reduce source energy use by 50,931 Mbtu per year
- reduce school district annual operating costs by $880,900

Advanced hybrid incremental cost estimates were developed based on the key system components. The IDEC and the instantaneous water heater are the most costly components of the $2,400 advanced hybrid system. The advanced hybrid incremental hardware cost of $1,586 is further increased by $200 to $1000 per unit based on the cost of connecting to an available properly sized gas line at the site. Although high heating load applications, such as climate zone 16, demonstrate simple paybacks as favorable as 4.6 years, the statewide average payback for the advanced RC is estimated at 9.9 years.

Advanced hybrid HVAC systems offer an efficient alternative to conventional HPACs. In addition to efficient space conditioning, advanced hybrid HVAC systems offer continuous high efficiency outdoor air ventilation. Unfortunately, the advanced hybrid technology evaluated in this study is not currently available as a packaged system. If a market develops for the advanced hybrid technology, competing products should appear and costs should decrease.

Although the advanced hybrid system offers significant energy efficiency benefits, there are issues to first address. The IDEC system requires more frequent maintenance than a standard HPAC. Evaporative media needs to be replaced, typically on 3-5 year intervals, and teachers and service personnel needs to be trained on the operational characteristics and maintenance requirements of the system. In addition, the IDEC will be hard-pressed to provide comfort in the extreme desert regions of California where mid-summer temperatures frequently exceed 110ºF and in year-round schools in the inland valley regions.

The advanced hybrid system offers great potential for improving the energy efficiency of RCs, while also improving IEQ. A larger scale field test of advanced hybrid systems would provide more data on system performance, installed costs, and teacher/staff satisfaction.

1 Background

This report addresses the results of detailed monitoring completed under Program Element 6 of Lawrence Berkeley National Laboratory's High Performance Commercial Building Systems (HPCBS) PIER program. The purpose of the Energy Simulations and Projected State-Wide Energy Savings project is to develop reasonable energy performance and cost models for high performance relocatable classrooms (RCs) across California climates. A key objective of the energy monitoring was to validate DOE2 simulations for comparison to initial DOE2 performance projections. The validated DOE2 model was then used to develop statewide savings projections by modeling base case and high performance RC operation in the 16 California climate zones.

The HPCBS energy efficient RC design is based upon earlier work by Davis Energy Group with Pacific Gas and Electric Company (PG&E), which culminated in the PG&E Premium Efficient Relocatable Classroom (PERC) program (DEG 1997). The envelope energy efficiency measures selected for the HPCBS project are similar to the PERC Package 1 except the HPCBS package substitutes a white ("Cool Roof") coating for the radiant barrier in the attic space. In addition to the standard wall-mount heat pump system (HPAC), the HPCBS RCs utilize an advanced hybrid system combining an Indirect/Direct Evaporative Cooler (IDEC), which provides two-stage evaporative cooling, and an instantaneous gas-fired heater and hydronic coil for heating.

Simulations described in this report add upon those conducted in program year one, with the benefit of data collected during the energy and indoor air and environmental quality (IEQ) field monitoring. Data from the field studies have been used to improve model inputs. The revised DOE2 analyses presented here provide an improved assessment of statewide energy performance for both base case and high performance RCs.

Since the initiation of this project a new revision of the California Title 24 Building Standards has begun (scheduled for release in 2005). As part of this process, RCs were examined and new code enforcement procedures were developed which will result in new RCs having envelope energy features very close to the HPCBS design. Table 1 summarizes key energy features of the HPCBS RC package. Additional background information on the construction details and assumed operating characteristics of RCs, as well as full-year DOE2 performance projections, can be found in the 2001 project report entitled Relocatable Classroom DOE2 Analysis Report, (Apte et al 2001, Shendell et al 2002).

Table 1: HPCBS Building Envelope Characteristics

Parameter	Value
Wall Insulation R-value	13
Floor Insulation R-value	19
Roof Insulation R-value	19
Glazing U-Value	0.48
Glazing Tvis	0.66
Glazing SHGC	0.49
Roof Absorptance	0.25 (white coating)
Roof Emissivity	0.95
Lighting Power Density	0.75 Watts/ft^2

2 Objectives

The primary objective of this phase of work was to utilize detailed field monitoring data to modify DOE2 inputs and generate performance projections based on a validated simulation model.

Additional objectives include the following:

1. Obtain comparative performance data on base case and high performance HVAC systems to determine how they are operated, how they perform, and how the occupants respond to the advanced systems. This was accomplished by installing both HVAC systems side-by-side (i.e., one per module of a standard two module, 24' by 40' RC) on the study RCs and switching HVAC operating modes on a weekly basis.

2. Develop projected statewide energy and demand impacts based on the validated DOE2 model.

3. Develop cost effectiveness projections for the high performance HVAC system in the 16 California climate zones.

3 Methodology

3.1 Overview

To accurately determine performance of the HPCBS HVAC system relative to the base case HPAC unit, a total of four RCs were tested in two locations (Modesto and Cupertino). Modesto is located in the Central Valley approximately 80 miles south of Sacramento, and Cupertino is located roughly 40 miles southeast of San Francisco. The climates are distinct, especially in the summer when Modesto experiences hotter, drier weather than Cupertino, which is moderated by its proximity to the Pacific Ocean. Table 2 summarizes ASHRAE design data for the two locations (ASHRAE 1982).

Table 2: Monitoring Site Design Weather Conditions

ASHRAE Design Condition	Cupertino	Modesto
Summer design dry bulb (0.5%*)	88ºF	99ºF
Coincident wet bulb	67ºF	70ºF
Summer daily temperature range	30ºF	30ºF
Winter design dry bulb (0.2%*)	33ºF	30ºF

* percentage values refer to the fraction of the year that temperatures are expected to be exceeded (0.5% = 44 hours, 0.2% = 18 hours).

The RCs at each site were used as standard elementary school classrooms, with Cupertino having about thirty 4th graders and Modesto having about twenty 3rd graders in each RC at full enrollment. Typical HVAC system operating hours were 8 AM to 3 PM (Modesto) and 8 or 9 AM to 4 PM (Cupertino). Normal day-to-day variations in operation occurred which caused some of the data to be excluded during data analyses. Monitoring of system performance occurred from September 2001 to June 2002. .

3.2 Description of HVAC Systems

Each of the RCs had two HVAC systems: a conventional wall-mount heat pump (HPAC) and an advanced hybrid HVAC system consisting of a two-stage evaporative cooler and a hydronic fan coil (advanced hybrid).

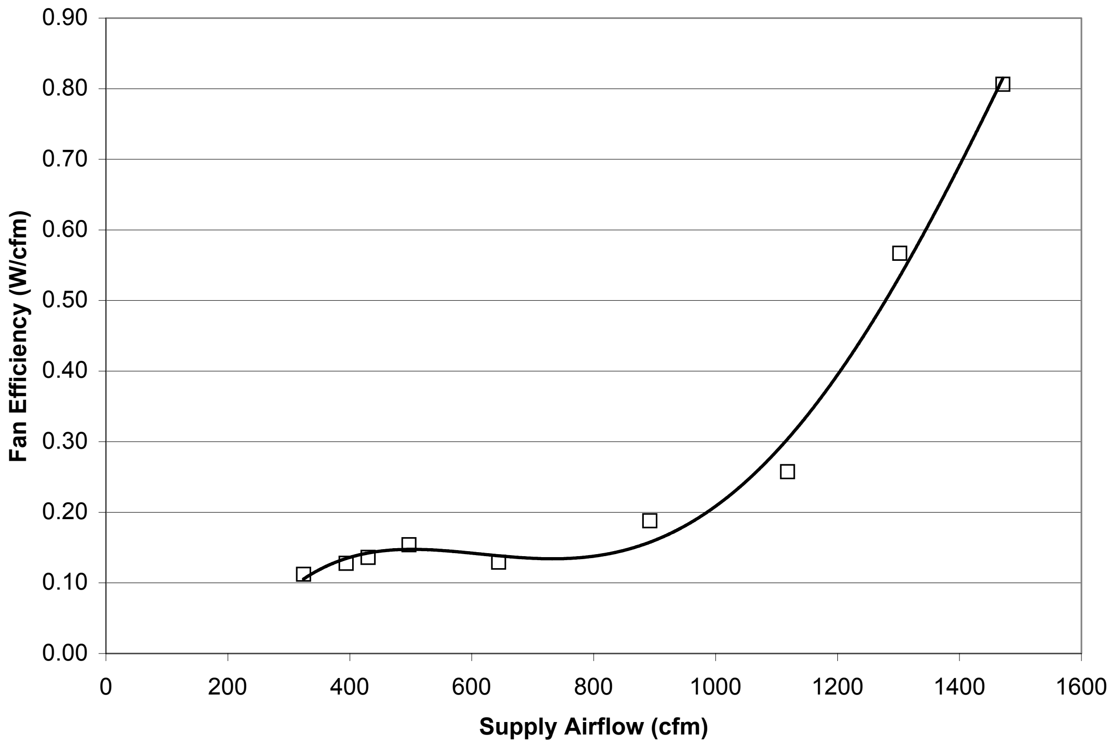
The conventional HPAC system was a standard 3.5 ton heat pump rated at 10 SEER and 6.8 HSPF with 10 kW of electric strip heat. Fan airflow was rated at 1400 CFM delivered through two 14" flex supply ducts. Outside air was provided by two ventilation options: at Modesto the HPAC used a barometric air damper which can deliver up to 25% outside air. At Cupertino, due to higher outside airflow rate required by the larger class size, a motorized damper was installed which can supply up to 50% outside air. Both districts used a commercial heating/cooling (non-heat pump) thermostat to operate the HPAC system. In addition, Cupertino added a four hour lock-out timer, which prevents the HPAC system from operating more than four hours after occupancy ends.

The advanced hybrid system consists of a two-stage evaporative cooler (IDEC) with a variable speed electronically commutated motor (ECM) capable of delivering 1500 CFM of air through three 12" flex ducts. Three high performance filters (Koch Filter Corporation, Louisville, KY) provided 65% ASHRAE Dust Spot Efficiency filtering of air. Heating was provided by a hydronic hot water coil sized to deliver 40,000 Btu at 750 cfm airflow and an entering air temperature of 32ºF. The 32ºF design temperature was selected since the system is always operating in 100% outdoor air mode to promote improved IEQ . Heat to the hydronic coil was provided by a pilotless (intermittent ignition device) 82% recovery efficiency instantaneous gas water heater[1].

[1] The 180,000 Btu/hour input unit has variable heating capacity ranging from 19,000 to 180,000.

The ECM motor operates efficiently at low airflow, making it an attractive choice as a supply air fan motor for the RC application, where much of the operation is at minimum outdoor airflow rates. The fan efficacy (expressed in terms of Watts/cfm) increases by a factor of five between full-speed operation and operation at typical outside air flow rates. Figure 1 plots monitored IDEC airflow delivery efficacy characteristics taken during testing.

Figure 1: IDEC Fan Efficacy vs. Supply Airflow



The advanced hybrid control is a modified version of the standard IDEC control. It has three lights indicating the mode (heat, cool, and auto), a single temperature slider, and a push button for selecting the mode. In heating mode, the supply fan operates at low speed to deliver the minimum outside air volume required. When the measured indoor air temperature drops below the set point, the hydronic pump is turned on and the water heater fires to maintain water supplied to the coil at 160°F. If the indoor air temperature drops more than 3°F below the set point the airflow is increased to 700 cfm to provide additional heating capacity. In cooling mode, the supply fan also operates at low speed to deliver the minimum outside air volume required. When the indoor air temperature rises above the set point, the IDEC pump is turned on to wet the direct and indirect media and then airflow is set proportional to the difference between the indoor air temperature and the thermostat set point. If the teacher chooses a low temperature setting on the IDEC thermostat, the ECM motor will run at maximum speed to try to achieve that setpoint. In auto mode the unit automatically enters cooling mode if the indoor air temperature rises 2°F above the set point and enters heating mode if the indoor air temperature drops 2°F below the set point.

Table 3 summarizes key operating characteristics of the base case HPAC system and the advanced hybrid system.

Table 3 HVAC System Operating Characteristics

	HPAC	Advanced Hybrid
Minimum outdoor air	Only when compressor on	Constant at 15 cfm/person
Heating mode operation	Compressor and fan "on," strip heat if needed	Maintain minimum outdoor air; activate pump and heater; increase cfm if unable to maintain setpoint (100% outdoor air)
Cooling mode operation	Compressor and fan "on"	Operates in fully variable speed mode in response to "indoor air to thermostat" temperature difference (100% outdoor air)

3.3 Data Analysis Methodology

A key goal in analyzing the monitoring data was to collect schedule data for the DOE2 validation work and to characterize HVAC system performance in terms of daily energy consumption as a function of daily average outdoor dry bulb temperature. System operating assumptions such as thermostat setpoints, operating hours, and outside air ventilation rates have a significant effect on annual energy consumption, and yet little reliable data had been collected for RCs. Although school districts frequently have guidelines on thermostat settings and schedules, actual thermostat control is often at the discretion of the teacher or custodian. Equipment may or may not be turned off during nights and weekends. Outside air dampers may not be set at the correct flow rate, and the system fans are typically operated only during thermal space conditioning, resulting in no outside air ventilation when cooling or heating demand is satisfied. Finally, door and window use, which affect ventilation, are difficult to define.

A subset of the IEQ monitoring data collected in this project was utilized in evaluating HVAC system performance. Temperature, relative humidity, power, gas use, and component status data were collected on six-minute intervals for each classroom; door and window opening data were also collected, but not used for this analysis. Prior to data analysis, three data cleaning and calculation steps were performed:

- Raw data were reviewed and bad data points were removed or corrected. Problems were encountered with data collection during the monitoring project start-up and sporadically during the monitoring. This resulted in some blocks of power and gas data being discarded.
- Fields not necessary for energy analysis were discarded.
- Six-minute data were aggregated into hourly and daily files. These were then combined into seasonal files with one file for each classroom.

With the monitoring approach of alternating HVAC system operation on a weekly basis, data were collected during fairly comparable weather patterns. Daily energy use totals were plotted against daily average outdoor air temperature. For the HPAC units, daily electrical energy use was plotted; for the advanced hybrid system, both electrical energy use and gas consumption were plotted. Although advanced hybrid continuous fan operation can provide improved IEQ, there are energy consequences, both in terms of increased fan energy consumption (though small) and increased RC space conditioning load.

Regression relationships were developed using daily average outdoor air temperature and indoor air temperature as the independent variables. These regression relationships were then used for both comparing the monitored energy use, eliminating any weather effects, and with full-year weather data to allow for comparison between DOE2 projections and the monitoring-based regression relationships.

Prior to completing comparative runs for the 16 California climate zones, the DOE2 model needed to be validated with the monitoring data. Reconciling daily variations in thermostat control with actual DOE2 inputs was a time consuming effort. To most closely mimic reality, the validation runs were completed with assumptions consistent with the field data. The primary impact was that for the advanced hybrid cases, the heating thermostat was maintained continuously (no setback) and minimum outdoor air was always being delivered during the heating season.

3.4 DOE2 Modeling

Prior DOE2 modeling utilized assumed thermostat and lighting schedules based on a combination of standard school models and a small sample of previously monitored RCs (DEG 2000). These assumptions were updated based on the monitoring data collected at the Cupertino and Modesto sites. More accurate schedules should improve the accuracy of savings projections. In prior analysis (DEG 2001), four different RC envelope/HVAC system configurations were modeled using DOE-2.1E release 130. The base case consisted of the standard envelope with the standard HPAC system and fan operation set to cycle on with compressor operation. The three comparison configurations were:

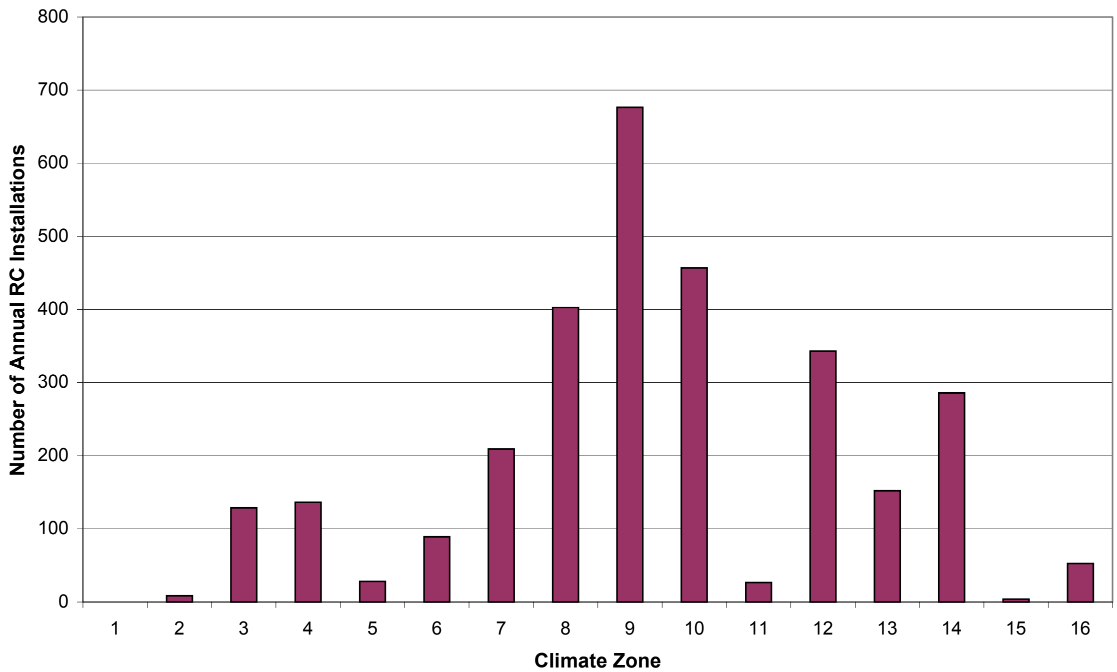
1) Standard envelope and HPAC system but constant fan operation to provide outside air flow to meet state code during occupied hours, which shows the energy impact of constant outside air.
2) Improved envelope with the standard HPAC system and a cycling fan (to demonstrate the impact of envelope measures alone).
3) Improved envelope with the advanced hybrid system (to demonstrate performance of the proposed package).

For this study, the base case was assumed to meet the upcoming 2005 Title 24 standards including an improved envelope, 12 SEER HPAC, and continuous fan operation. Simulations were completed using lighting and thermostat schedules determined from the field monitoring. These simulations were completed assuming traditional school year schedules, not year-round schedules. This assumption should generate conservative savings estimates as annual cooling loads are lower for the traditional school schedule.

3.5 Statewide Projections

An important objective of this project is to extrapolate performance and savings to a statewide basis. Annual estimates of California RC construction are approximately 4,000 units per year (CARB 2003), although class size reduction programs have boosted RC construction levels to close to 10,000 in previous years. Analyzing California Department of Education data showing K-12 enrollment projections by county, we have generated estimates of RC placement on a climate zone basis. Figure 2 plots where the projected 4,000 RCs built annually will be installed. The greater Los Angeles area (climate zones 8-10) is projected to account for over half of annual RC installations.

Figure 2: Projected Annual RC Installations by Climate Zone



To determine statewide energy demand impacts, RC simulations were completed for each of the 16 climate zones for both HPAC systems (nominal 6.8 HSPF, 12 SEER) and advanced hybrid systems. Statewide projections were determined by factoring the "per unit" impacts by the expected number of installations in each climate zone. Operating cost savings were computed based on statewide average commercial electric rate of \$.1487/kWh[2] and an assumed statewide average of \$.74 per therm[3].

[2] www.energy.ca.gov/electricity/statewide_weightavg_sector.html

[3] Monthly weighted California commercial gas rates from EIA for December 2001 to November 2002 average \$.60/therm (see www.eia.doe.gov/emeu/states/ngprices/ngprices_ca.html), however short-term expectations for natural gas prices are considerably higher. The more conservative \$.74 per therm assumption is based on PG&E G-NR1 rates over the previous twelve months.

Statewide runs were completed to insure comparable loads and IEQ conditions in both cases. Table 4 summarizes DOE2 inputs for these runs. Two key areas where the statewide simulations will demonstrate improved energy savings relative to the monitoring results are the incorporation of continuous outdoor air during occupied periods and elimination of heating operation during non-occupied periods.

Table 4: DOE2 Inputs for Statewide Simulations

Parameter	DOE2 Input
Occupancy period	8 AM-4 PM weekdays, standard school year
Outdoor air during occupancy	315 cfm (21 people @ 15 cfm/person)
Minimum outdoor air fan power	50 W (advanced hybrid), 560 W (HPAC)
Heating Setpoint/Setback/Weekends	70ºF / 65ºF / 60ºF
Cooling Setpoint/Setback/Weekends	74ºF / 85ºF / 85ºF

4 Results

4.1 HVAC Controls Issues

Understanding how individual teachers control the HVAC systems is critical to analyzing HVAC system energy use. Of the two controls, the advanced hybrid thermostat is the simplest, with one setpoint and three modes, but its interaction with the system is the most complex and it was unfamiliar to the teachers – leading to unforeseen energy impacts. The HPAC thermostat was also simple, with no setback capabilities, but it too had significant impact on the HPAC energy use.

Control operation had the largest impact on the advanced hybrid heating use. Initially, in the first week of heating the advanced hybrid systems demonstrated inadequate heating capacity due to a combination of low hot water heater set point and construction debris reducing the water flow rate through the piping. To counteract the low capacity, teachers left the systems running in heat mode overnight to minimize the morning pickup load. This operating behavior continued even after the system problems were corrected, leading to higher monitored gas usage.

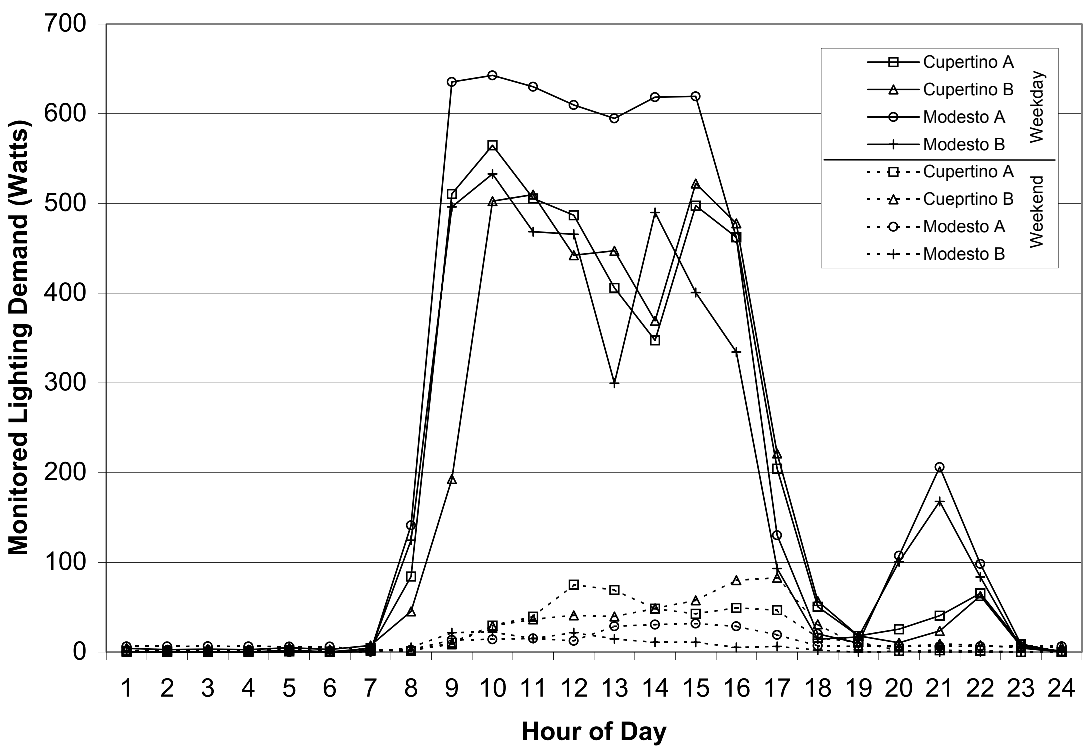
As has been observed in previous RC monitoring projects, the HPAC thermostat was operated almost exclusively in the “auto” fan mode. In this mode, the fan (and minimum outdoor air) only comes on during compressor operation. In heating mode, data suggested the teachers were using the thermostat as a “switch,” turning it to heat mode with a high set point when indoor conditions became cool. The consequence of this behavior was an average of 80% of the heating energy use was due to the electric strip heat. Data also showed numerous instances of the HPAC system running for 1-2 hours after occupancy had ended and then shutting off, suggesting that the lock-out timers were highly effective.

4.2 Monitored Lighting and Thermostat Schedules

Prior DOE2 modeling assumed “typical” usage schedules and fixed thermostat setpoints during occupancy. Assumed heating thermostat setpoints were 70ºF during weekday occupancy period (8 AM to 4 PM) with 65ºF night setback, and 60ºF fixed setpoint on weekends and holidays. Assumed cooling setpoints were 76ºF during normal occupancy, and 85ºF for other hours.

Monitoring data from the four RCs reflected the impact of real world operation and the impact the teachers had on overall energy use. Lighting controls for the three lamp T8 fixtures include switching to operate one lamp, two lamps, or three lamps. Figure 3 plots average weekday and weekend (including holidays) lighting demand for the four RCs for the entire monitoring period[4]. Three of the four average weekday plots show very similar operation with a morning rise, lower use during the day including a drop at lunch, and then a second rise at the end of the school day. The fourth site, Modesto RC A, demonstrated a much flatter profile at an average demand 35% higher than the other three sites, which indicated the impact of teacher behavior on actual lighting levels. The small peaks at 21:00 and 22:00 are due to classroom cleaning by the janitorial staff. The small weekend peaks at midday in Cupertino RC A and in the afternoon in Cupertino RC B were likely due to teachers working to prepare for the upcoming week's lessons.

Figure 3: Monitored Lighting Profiles for All Classrooms



[4] Monthly and seasonal variations in the lighting profile were not significant (<10%) after accounting for holidays and vacations days, due to the monitored RCs lack of significant daylighting.

Figure 4 plots overall averages of the monitored weekday/weekend lighting schedules. This averaged profile was used in DOE2 for annual energy use projections. The original "estimated" profiles are also plotted for comparison. Except for the dip at noon and the evening use, the profiles are very similar and the impact of using the new profile will be small.

Figure 4: Average Monitored Lighting Profiles

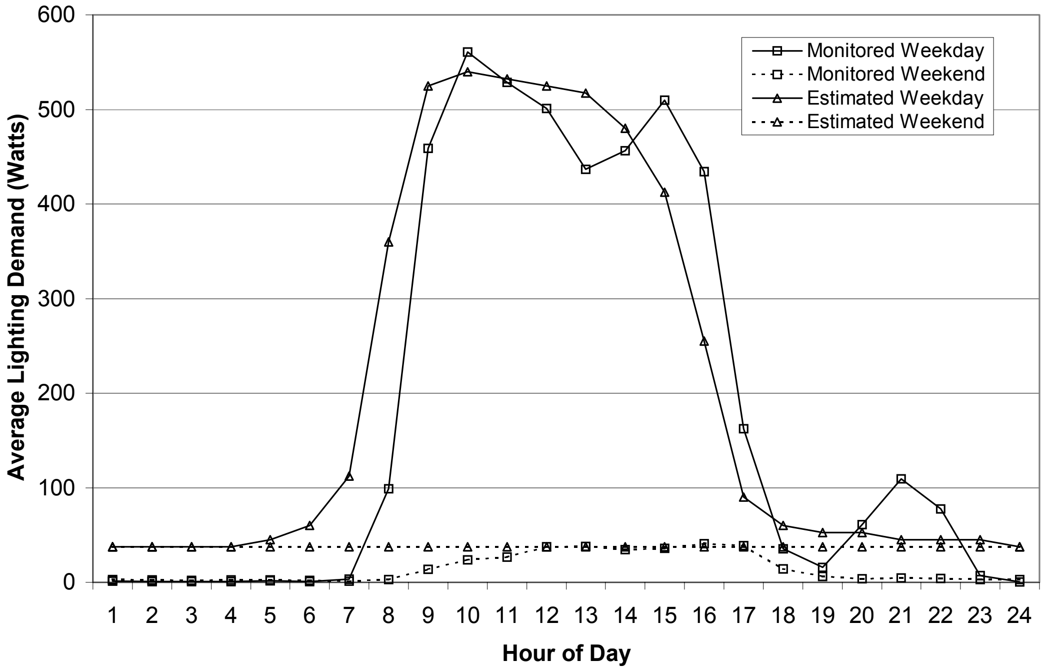
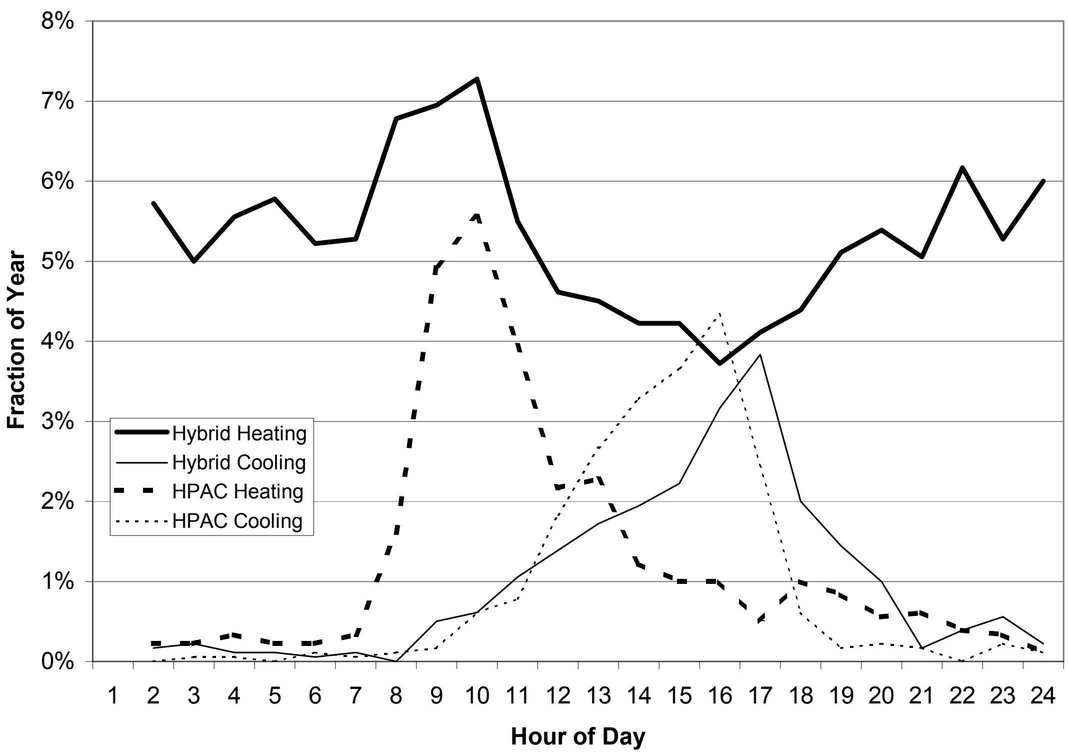


Figure 5 plots monitored thermostat setpoints for both the HPAC and the advanced hybrid HVAC systems. Since thermostat setpoint is not directly monitored, it was calculated by determining the indoor air temperature when the operating cycle ended (i.e., thermostat was satisfied). Data were plotted for heating and cooling operation modes. Missing data indicated hours for which no "end of cycle" points were recorded and the system was presumed to not be operating. The advanced hybrid heating data indicate continuous operation throughout the day. HPAC cooling data indicate that at the end of the day the unit was not immediately turned off (dips below 66ºF at hour 18) due to the operation of the four-hour lock-out timer.

Figure 6 renders this data in a slightly different format to demonstrate when HVAC operating cycles were most commonly terminated. Conventional HPAC operation shows a pattern consistent with expected space condition loads. A majority of the heating cycles terminated in the mid- to late morning, while cooling cycle termination increased towards the end of the school day. The advanced hybrid system demonstrated a different pattern. Due to the previously mentioned temporary low heating capacity problems, some of the teachers left the system operating continuously, even after the problems had been corrected, resulting in a fairly flat cycle termination profile. The advanced hybrid system shows a cooling pattern similar to HPAC cooling, although with a slightly broader period of cooling.

Figure 5: Monitored Temperature at Termination of HVAC Operating Cycle

Figure 6: Frequency of HVAC Cycle Termination vs. Time of Day

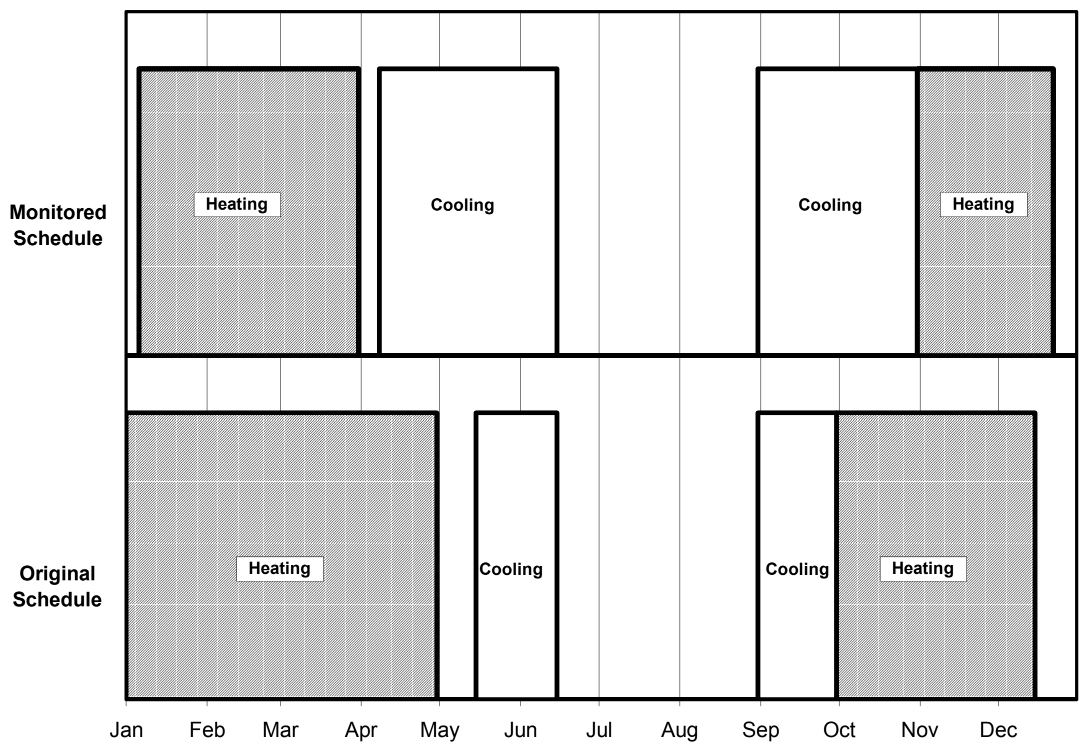


On average, the HPAC system heating setpoints were found to be 1ºF higher than for the advanced hybrid system, and HPAC system cooling setpoints were found to be 1ºF lower. This reduction in the thermostat deadband (the temperature difference between heating and cooling setpoints) was significantly less than assumed in the original DOE2 model.

For the revised DOE2 modeling, this reduced deadband was modeled based on the observed thermostat operation.

Figure 7 compares the seasonal schedules used for the original DOE-2 simulations and those developed from the monitoring data. The principle difference is the longer cooling seasons observed with some minor differences in length and location of breaks. The school year starts August 30th in cooling mode, with heating mode starting after October 31st until the beginning of winter break, December 15th. The heating mode continues from January 6th to the end of spring break (March 29th in Modesto and April 13th in Cupertino) and the cooling mode was assumed for the remainder of the school year. By assuming a switch from heating to cooling mode operation, our DOE2 modeling will slightly underestimate swing season space conditioning energy use.

Figure 7: Yearly Operation Schedules (Traditional School Year)



4.3 Monitored Space Conditioning Energy Use

Figures 8-10 present monitored daily energy use in both heating and cooling modes for the two system types and two climates. Electrical energy use for the advanced hybrid is comprised of fan energy, both during heating cycles and for providing continuous outdoor air, and a small amount of pumping energy. The advanced hybrid consumes only about 50 Watts of fan energy when operating in outdoor air ventilation mode. The winter impact on gas use, however, can be significant if the system is operated to maintain temperature 24 hours a day. Simulation results presented in subsequent sections provides source energy comparisons for the two system types.

Figure 8 plots daily electric energy use for heating for the base case HPAC system and the advanced hybrid system (gas use is displayed in Figure 9). Monitored HPAC system energy use was higher for Modesto than for Cupertino, due both to colder winter weather and also fewer students (lower internal gains). Advanced hybrid system electrical energy use was considerably lower than for the HPAC units, since only fan and pumping energy was included. Cupertino advanced hybrid system energy use was slightly higher than in Modesto, probably due to higher internal and ventilation air loads.

Figure 8: Monitored Daily RC Heating Electrical Energy Consumption

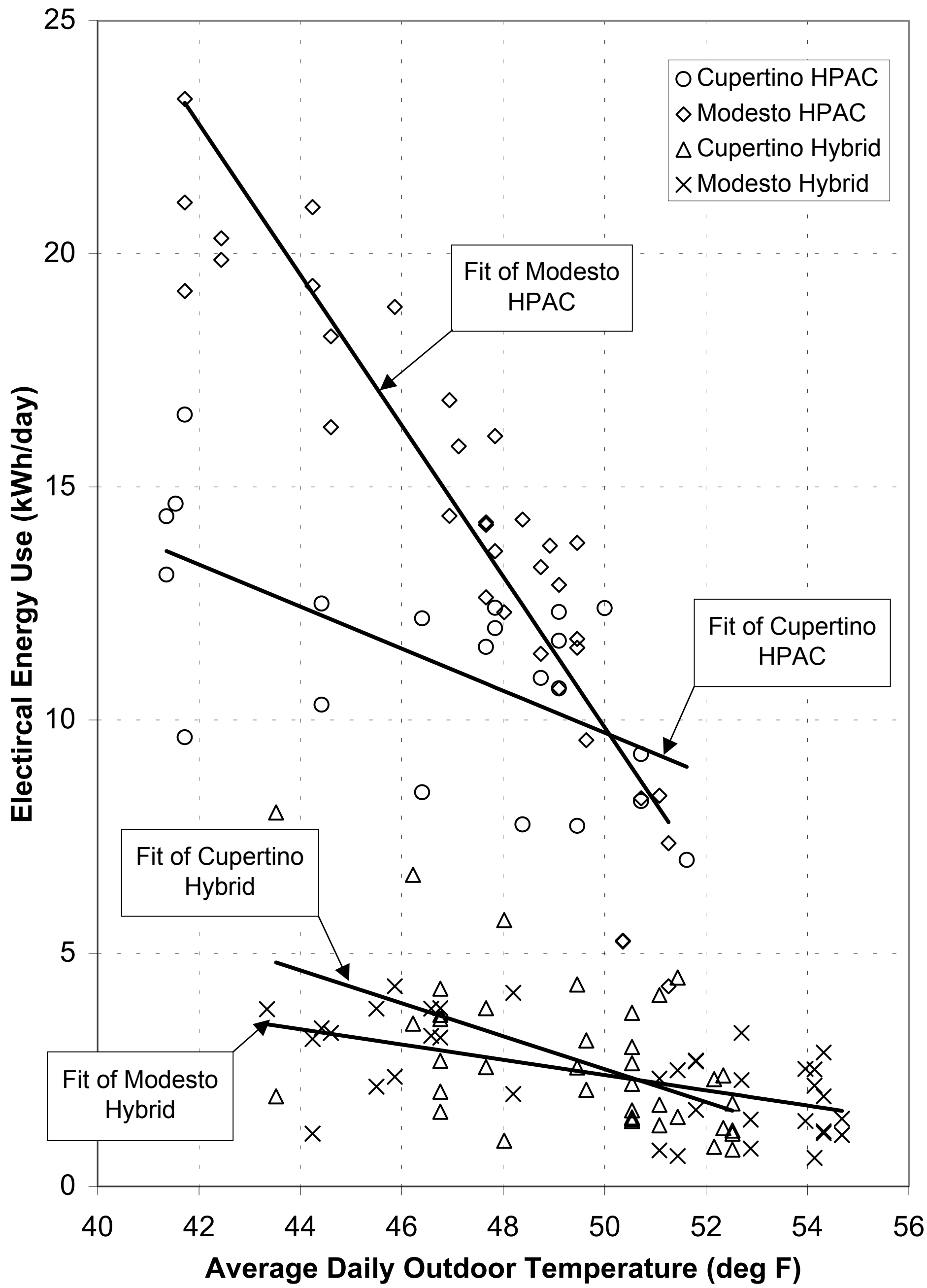


Figure 9 plots daily heating gas energy use for the advanced hybrid instantaneous gas heater. The Cupertino gas use was higher than in Modesto, which was most likely due to continuous heating operation at a higher ventilation airflow rate. In completing statewide projections, DOE2 simulations will compare performance with both base case and high performance systems providing minimum outdoor air during occupied hours only.

Figure 9: Monitored Daily RC Heating Gas Energy Consumption

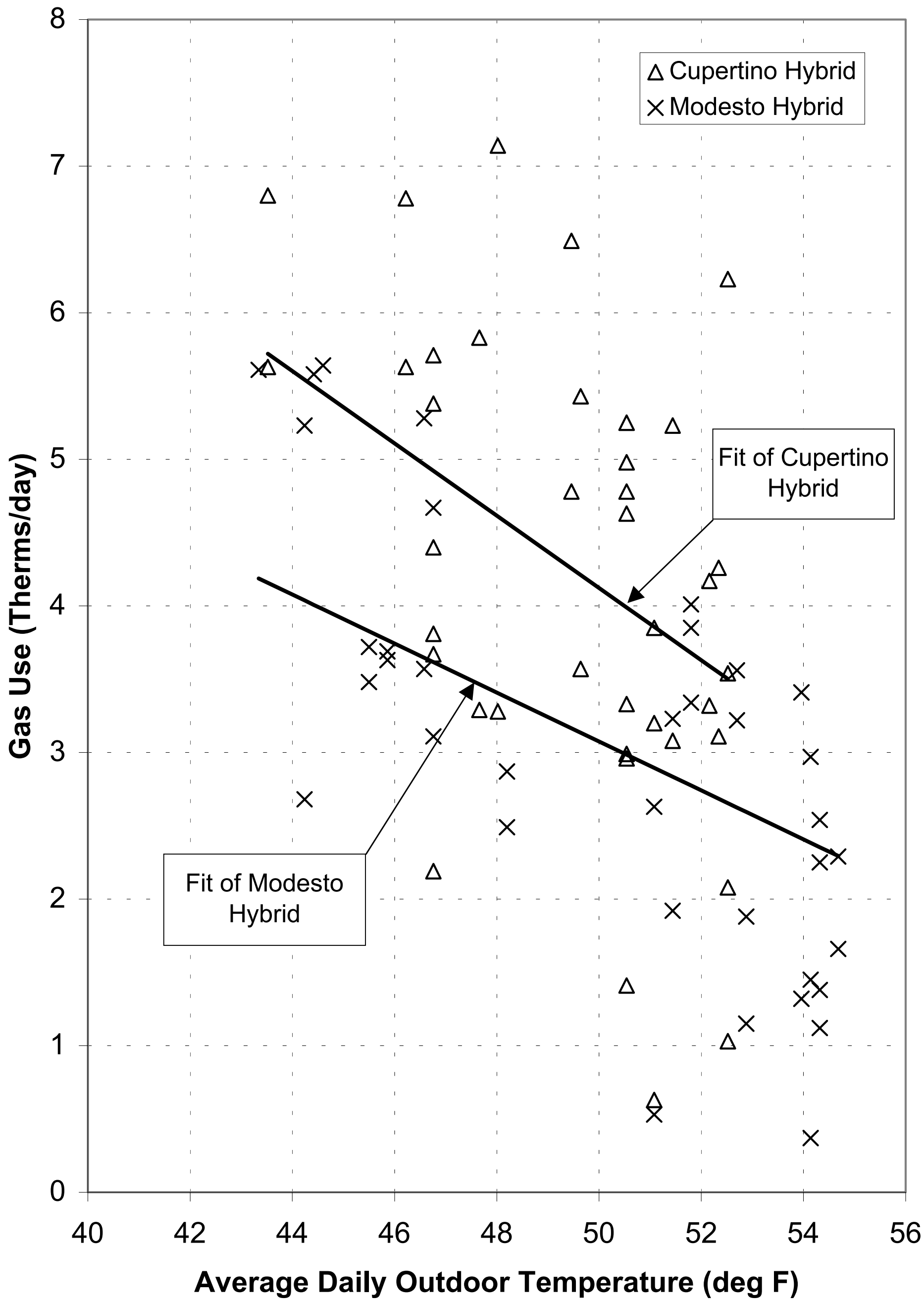
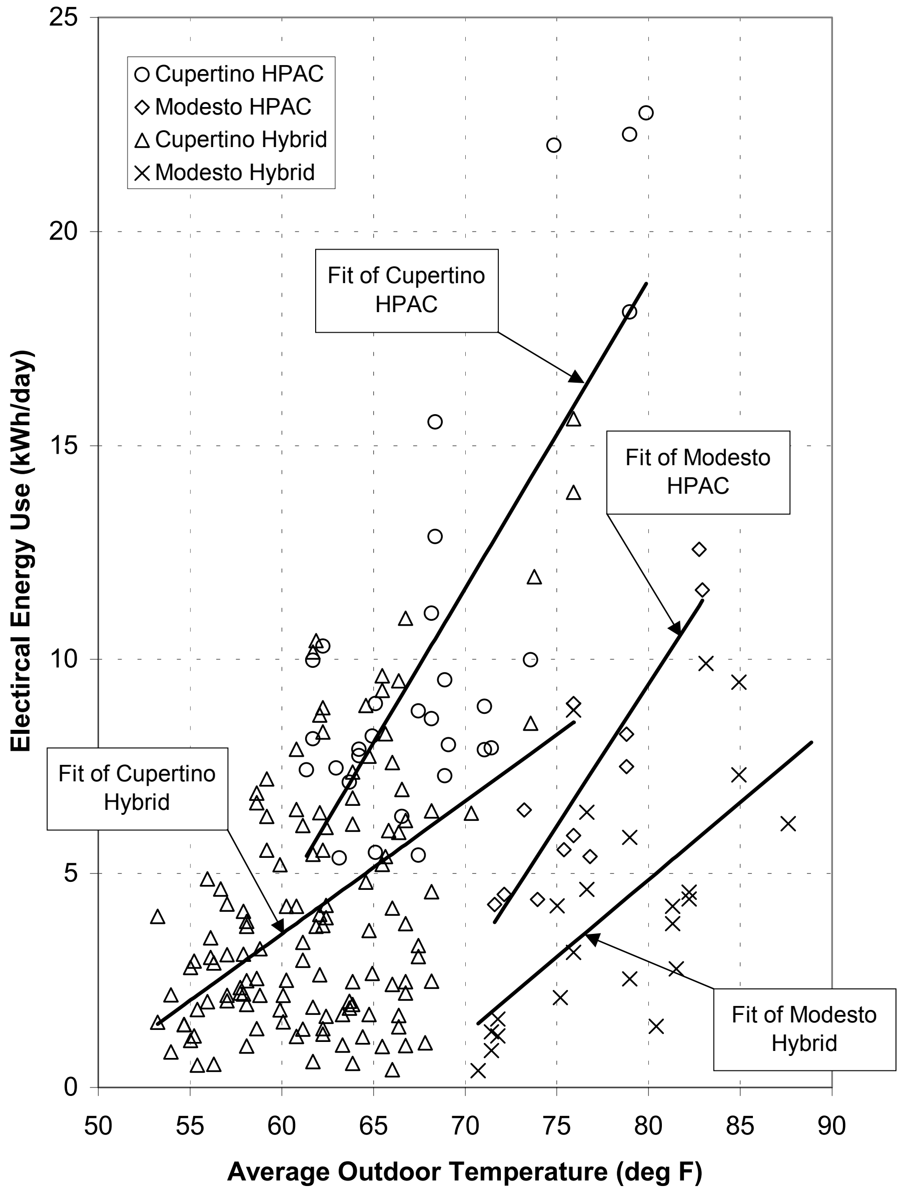


Figure 10 plots cooling electrical energy use for the two system types in both locations. The Cupertino RCs displayed cooling energy use at lower average temperatures than the Modesto RCs. Although the magnitude of the difference is greater than anticipated, two factors likely contributed to this. First, the higher internal gains in the Cupertino RCs due

Figure 10: Monitored Daily RC Cooling Electrical Energy Consumption



to 50% higher enrollments, and the influence of teacher preferences, resulted in the need for cooling at lower temperatures. Second, the higher outdoor air ventilation rates at Cupertino would contribute to afternoon cooling loads earlier than in Modesto. Given the fewer data points for Modesto, we have greater confidence in the validity of the

Cupertino regression relationships. Advanced hybrid data demonstrated savings in both locations, consistent with our expectation of how the IDEC unit should perform[5].

Table 5 summarizes the linear fits to the regression lines shown in Figures 8-10. Advanced hybrid system gas use was also found to be statistically dependent on indoor air temperature, which acts as an indicator of continuous operation. These regression equations are used to project annual energy usage at both Cupertino and Modesto for the model validation comparisons.

Table 5: Summary of Energy Use Regressions

	Constant	*Toutdoor Coefficient*	*Tindoor Coefficient*	*R^2*	*Number of points*
Cupertino					
HPAC					
Heating	32.3	-0.451		39%	21
Cooling	-38.9	0.722		58%	29
Advanced Hybrid					
Heating	20.2	-0.353		30%	38
Cooling	-15.1	0.311		23%	125
Gas Use	3.4	-0.271	0.215	66%	154
Modesto					
HPAC					
Heating	90.7	-1.617		84%	35
Cooling	-43.6	0.663		80%	11
Advanced Hybrid					
Heating	10.6	-0.164		35%	36
Cooling	-24.0	0.361		41%	22
Gas Use	-0.52	-0.149	0.158	90%	76

Table 6 summarizes extrapolated full-year energy use at Cupertino and Modesto based on actual weather data. The results compensate for the weekly switching of HVAC system type. As previously discussed, Modesto cooling energy use was considerably lower than at Cupertino. The advanced hybrid system demonstrated electrical savings in both locations, although projected full-year gas use was high due to heating during unoccupied periods. For the four study RCs, only 22% of monitored gas use occurred during occupied hours.

Figure 11 plots averaged hourly electrical demand for the HPAC and advanced hybrid systems in both heating and cooling operating modes. (Appendix A figures A2-A5 contain profiles from each of the four sites, which were averaged to generated Figure 11.) The plotted data averages the hourly demand over the most extreme days (based on average outdoor air temperature) for each season[6]. The plot is intended to demonstrate

[5] As dry bulb temperatures increase, wet bulb depression also increases, which should contribute to improved performance (greater savings) relative to vapor compression systems at higher ambient temperatures.

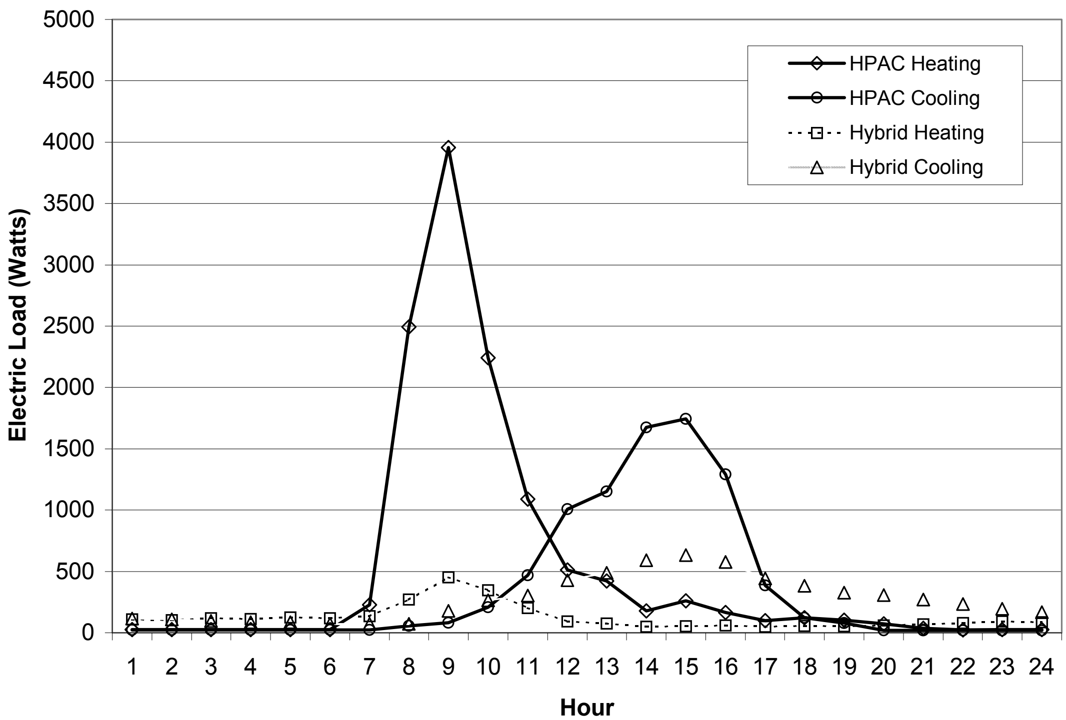
[6] Between nine and 21 days were averaged to compile this plot.

the characteristic average demand profile of the two system types. The extreme days were selected to avoid the complications associated with days in which both heating and cooling operation occurred. On average, the advanced hybrid system reduced peak heating electricity demand by 89% and peak cooling demand by 64%.

Table 6: Projected Annual Energy Use (Actual Site Weather)

Energy Use	*Electric (kWh)* *HPAC*	*IDEC*	*Gas (therms)* *IDEC*
Cupertino			
Heating	352	94	223
Cooling	569	389	
Total	922	483	223
Modesto			
Heating	516	115	168
Cooling	206	91	
Total	722	206	168

Figure 11: Average HPAC and Advanced Hybrid Hourly Demand Profiles



4.4 Comparison of DOE2 and Monitored Space Conditioning Energy Use

DOE2 model validation is needed to ensure the statewide simulation runs generate results consistent with the monitoring data. To complete this exercise, regression relationships in Table 5 were combined with DOE2 TMY weather files (Sunnyvale was used for

Cupertino and Fresno for Modesto) to predict full-year consumption. Monthly usage was compared to DOE2 simulations of HPAC and advanced hybrid systems operation using the same weather locations. DOE2 simulations were completed assuming heating and cooling operation during non-occupied periods (consistent with the overall monitoring data). For calibration purposes HPAC system heating and cooling electric input ratios (EIR's) were adjusted from the original manufacturer's assumptions to values obtained from the full-season monitoring data. To achieve this, the 47ºF heating coefficient of performance (COP) DOE-2 input was de-rated from 3.2 to 1.9. This large degradation is primarily due to much higher monitored strip heat energy usage and unaccounted for jacket loses. Similarly, cooling EER (at 95ºF) was de-rated from the nominal 9.25 EER to a 7 EER. Figures 12-15 compare monthly heating and cooling energy use for Cupertino and Modesto based on these assumptions. (See Appendix A for more data on monitored HPAC system performance.)

Figure 12: Cupertino Heating Energy Comparison

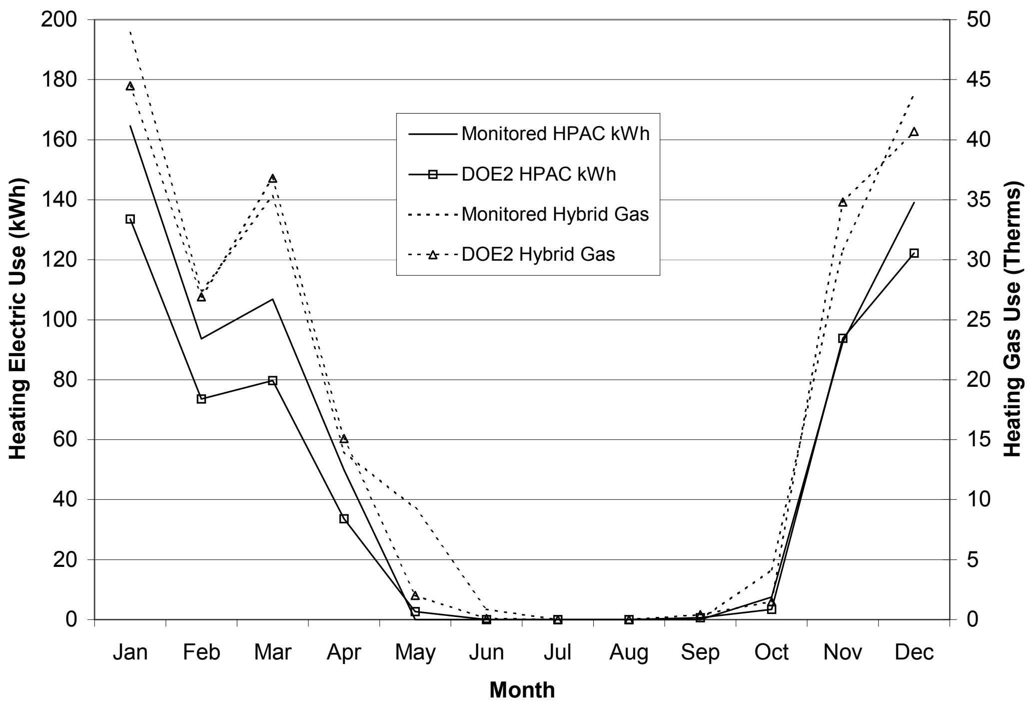


Figure 13: Cupertino Cooling Energy Comparison

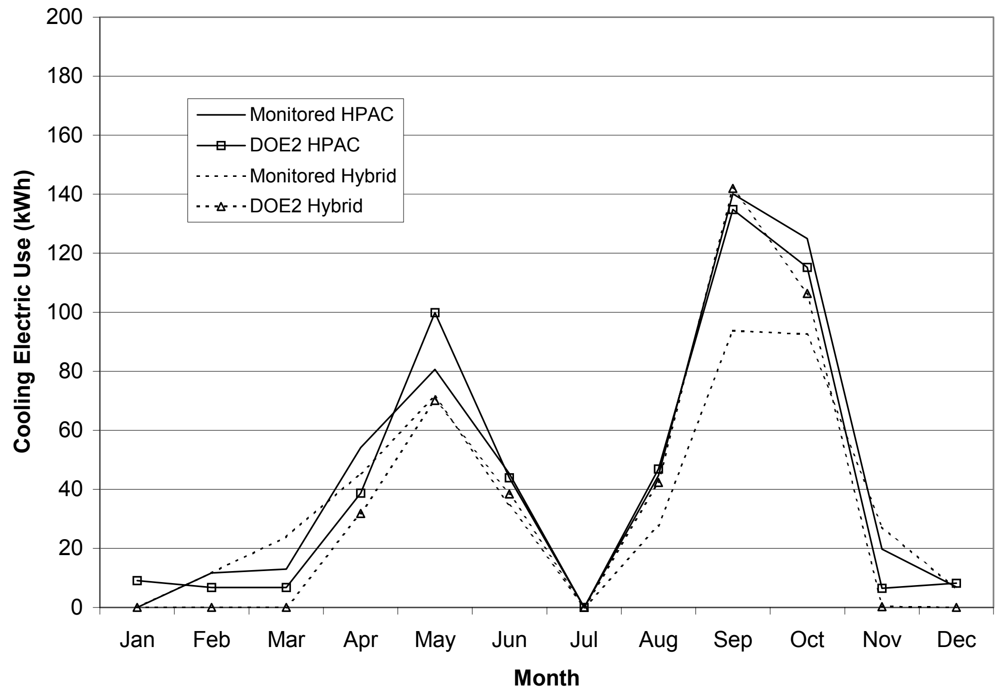


Figure 14: Modesto Heating Energy Comparison

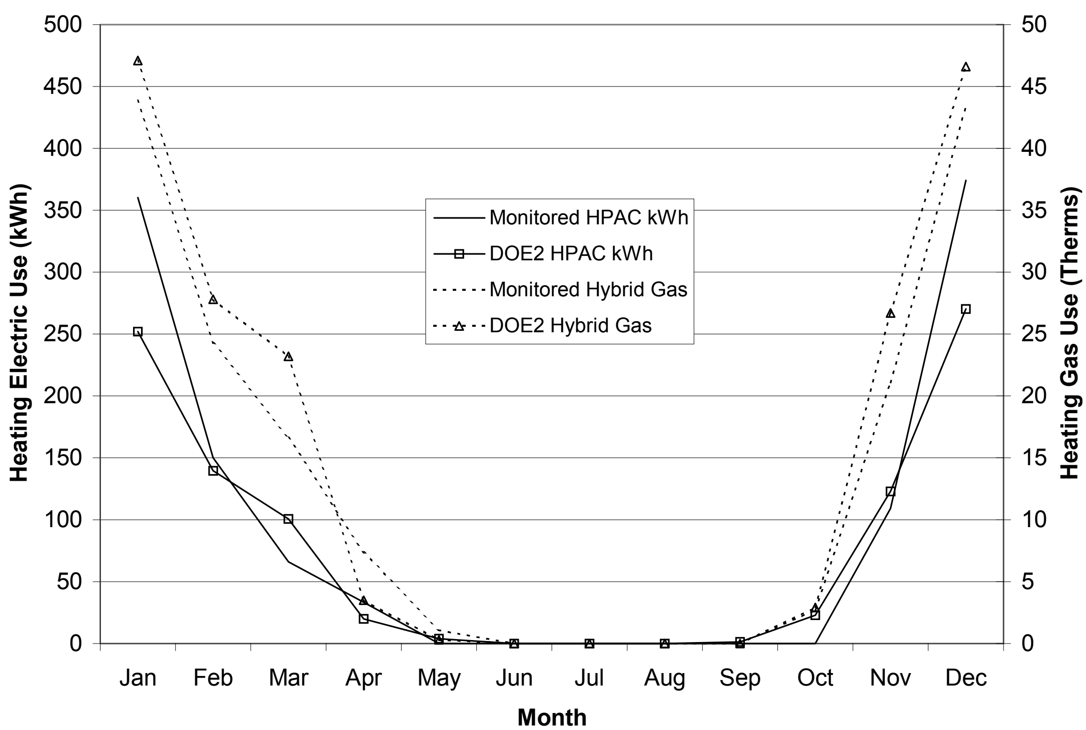
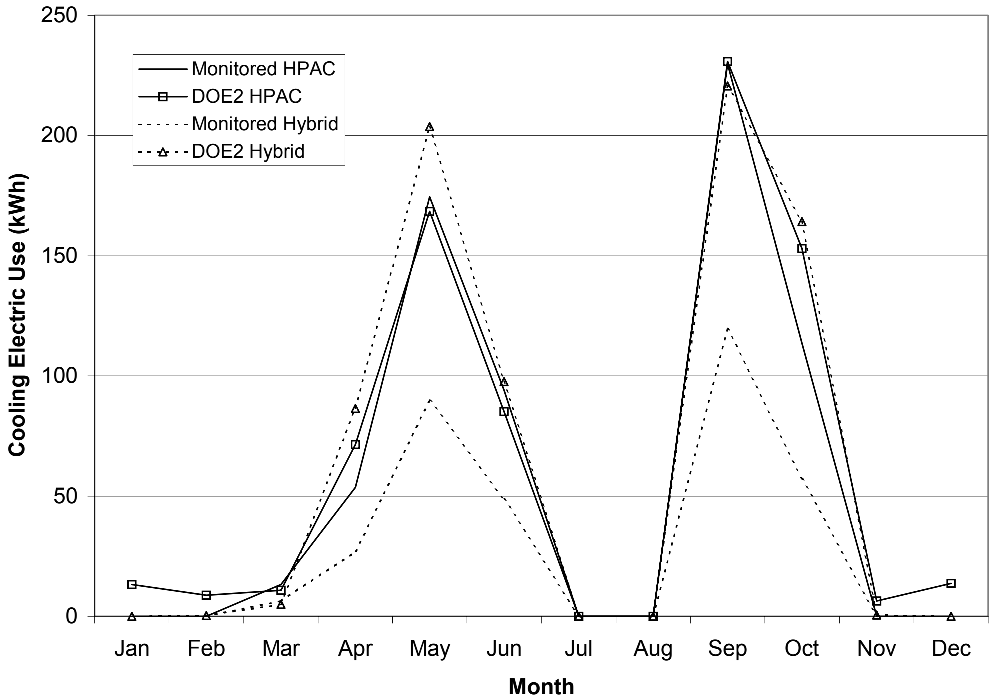


Figure 15: Modesto Cooling Energy Comparison



The comparisons of monthly "actual" and "simulated" energy use is fairly close. DOE2 tends to slightly underestimate HPAC system heating energy use (e.g., Cupertino winter) as it is difficult for the program to accurately resolve strip heat operation with an hourly time step[7]. The difference between monitored and DOE2 values in Cupertino in May (Figure 13) may be due to increased use of doors and windows for natural ventilation. Advanced hybrid system cooling is complicated by the impact of varying fan efficiency (Watts/cfm) with airflow. If the teacher adjusts the advanced hybrid system control to achieve a lower temperature, the effect would be to operate the system at a higher airflow rate, and less efficiently, than would normally be the case.

The DOE2 projections for cooling are higher than the monitored cooling energy usage. This is due to the varying schedule of cooling operation, with some days showing continuous hybrid operation and some only during occupied hours. The DOE-2 simulations assume the hybrid system is on constantly for weekdays. Given the Cupertino comparison is fairly good and the data supporting the Cupertino regression relationship is more robust, we feel comfortable in claiming the DOE2 model provides a good match with the monitored results. We recognize the shortcomings of this assumption, but the errors introduced are conservative in that it results in higher simulated IDEC cooling use and lower simulated HPAC heating use.

[7] The six minute monitoring data clearly demonstrated frequent strip heat operation even during hours when the full-hour load is not large. An hourly model does not have the resolution to accurately resolve this.

4.5 Statewide Performance Projections

Statewide projections were completed for base case HPAC and advanced hybrid systems. As discussed in section 3.5, standardized inputs were applied to both system types to ensure comparable loads, unlike the field monitoring results. Consistent with RC requirements under the proposed 2005 Title 24 Standards, minimum outdoor air ventilation was modeled during occupied hours. This assumption impacts the HPAC system significantly since the single-speed fan must operate at a fixed 560 Watt demand, while the advanced hybrid can provide the same amount of outdoor air with only a 50 Watt demand. Appendix B contains a complete summary of the results for each of California's 16 climate zones, while the body of the report focuses only on three zones with large RC growth potential: 3 (mild San Francisco Bay area), 9 (inland Southern California), and 12 (hot inland valley, e.g., Modesto).

Table 7 summarizes projected annual energy performance for the two system types in the three climate zones. Advanced hybrid system heating and cooling energy represents pump and controls energy only; fan energy represents blower operation. Advanced hybrid system electricity savings in these three zones were significant, exceeding 80%. DOE2 projected HPAC system cooling demands were much lower than monitored data suggested, due to assumptions inherent in an hourly time-step simulation. To more accurately reflect real performance, HPAC system cooling demands were calculated using a regression relationship based on the monitored performance of the HPAC heat pump versus outdoor air temperature (see Figure A-7 in Appendix A) and the ASHRAE 0.5% summer design temperatures for the representative cities. Advanced hybrid demand does not vary with temperature and therefore this step was not necessary. Projected cooling demand savings exceeded 70% in these three climate zones.

Table 7: Annual HVAC Energy Use and Demand Projections [8]

System		Annual kWh				Peak kW		Gas Use
Type	CZ	Heating	Cooling	Fan	Total	Heating	Cooling	therms/yr
HPAC	3	519	187	868	1574	4.2	4.4	0
Hybrid	3	15	5	157	177	0.2	1.3	26
HPAC	9	340	483	833	1656	5.6	4.6	0
Hybrid	9	10	17	308	335	0.2	1.3	18
HPAC	12	833	362	902	2097	7.4	4.7	0
Hybrid	12	22	13	272	307	0.2	1.3	43

Table 8 reports annual HVAC source energy (based on a heat rate of 10.239 kBtu/kWh), annual space conditioning operation costs, and projected energy and operating cost savings. For the three zones, source energy savings exceeded 65% and operating cost savings exceeded 74%. Figure 16 provides a source energy comparison for the three climate zones (Oakland =3, Burbank =9, and Sacramento =12) with end uses

[8] HPAC "heating" includes compressor and strip heat; HPAC "cooling" includes compressor; HPAC "fan" represents all fan energy. Hybrid "heating" and "cooling" represents only the pumping energy; "fan" represents all fan energy.

disaggregated. Advanced hybrid system cooling energy use is shown as fan energy, in contrast to the HPAC system where compressor energy use is shown for cooling.

Table 8: Annual HVAC Source Energy, Cost, and Savings Projections

System Type	CZ	Source Energy MBtu	Annual Cost	Savings MBtu	Savings Cost	Savings (%) MBtu	Savings (%) Cost
HPAC	3	16.1	$234	--	--	--	--
Hybrid	3	4.4	$46	11.7	$188	73%	81%
HPAC	9	17.0	$246	--	--	--	--
Hybrid	9	5.3	$63	11.7	$183	69%	74%
HPAC	12	21.5	$312	--	--	--	--
Hybrid	12	7.5	$77	14.0	$234	65%	75%

Figure 16: Source Energy Savings for Advanced Hybrid vs. HPAC

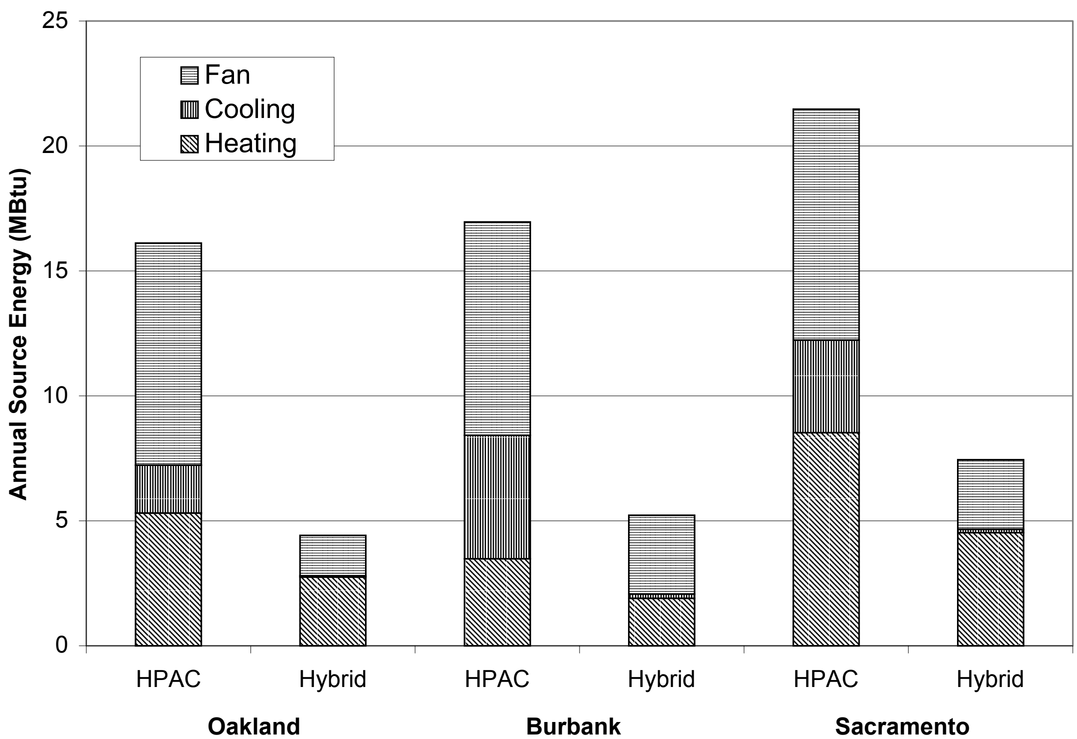


Table 9 tabulates the technical potential of replacing HPAC systems with advanced hybrid systems based on our projected placement of 4,000 RCs annually. Climate zone impacts were totaled based on the projected climate zone distribution of new RCs shown in Figure 2. Projected impacts on a statewide basis were source energy and operating cost savings exceeding 80% and demand reductions exceeding 70%. Ten year cumulative impacts are also shown reflecting the impact of 4,000 hybrid units per year. Weighted statewide average “per unit” annual impacts amounted to:

- 1,494 kWh electricity saved (82% reduction)
- 5.9 kW winter peak electric load reduction (96% reduction)
- 3.3 kW summer peak electric load reduction (72% reduction)
- 26 therm gas increase
- 13 MBtu source energy savings (69% reduction)
- $220 annual operating cost savings, ranging from $159 to $385 (82% reduction)

Table 9: Annual Statewide HVAC Source Energy, Cost, and Savings Projections

System Type	Electric Use (MWh)	Gas Use (MBtu)	Peak Demand Heating (MW)	Peak Demand Cooling (MW)	Source Energy (Mbtu)	Annual Operating Cost
HPAC	7,253	0	24.7	18.3	74,261	$1,078,500
Hybrid	1,278	10,247	0.9	5.2	23,330	$197,600
Savings:						
Year 1	5,975	(10,247)	23.8	13.1	50,931	$880,900
%	82%	n/a	96%	72%	69%	82%
Year 10	329 GWh	(0.56 Tbtu)	238	131	2.8 TBtu	$48,500,000

Table 10 estimates incremental costs for the advanced hybrid system relative to the 6.8 HSPF/12 SEER HPAC unit. A challenging cost variable is the cost of connecting gas to the RCs. The instantaneous gas-fired water heaters require larger than typical gas line sizing due to their high capacity output, even though less than 25% of their full capacity is required by the heating coil. Our estimates assumed a minimum of 10 RCs are placed in close proximity to one another. We estimated a range in gas line costs with the high estimate based on the actual $10,000 extension cost, while the low estimate assumed a lower capacity water heater with a resulting smaller gas line sizing. Final incremental cost estimates ranged from $1,786 to $2,586 per unit. Expectations are that the advanced hybrid system incremental costs would come down if production volumes increase.

Table 10: Advanced Hybrid System Estimated Incremental Costs

Item	Estimated Cost
IDEC	$1,200
Instantaneous water heater	$800
Coil, pump, expansion tank	$220
Incremental labor	$200
Subtotal	$2,420
12 SEER HPAC	($1,200)
Net Cost	$1,220
RC manufacturer markup	$366 (30%)
Gas line extension cost	$200-$1000
Total Incremental Cost	**$1,786 - $2,586**

On a weighted statewide basis, the advanced hybrid system is projected to have a simple payback ranging from 8.1 to 11.7 years, depending gas line extension costs. Projected simple paybacks calculated by climate zone are shown in Table 11 based on the range of incremental costs shown in Table 10 for those climate zones where 200 or more RCs are placed annually[9]. Although paybacks as low as 4.6 years are projected for the mountainous climate zone 16, the more populous zones have longer paybacks due to lower loads (and savings). Based on average advanced hybrid system incremental cost, an average 10.6 year payback is projected for the more populous zones listed in Table 11.

Table 11: Advanced Hybrid Projected Simple Payback

Climate Zone	Estimated RC Units /year	Simple Payback Range (years)
14	381	6.9 to 9.9
13	203	7.4 to 10.7
12	457	7.6 to 11.0
10	609	9.5 to 13.7
9	902	9.8 to 14.1
8	537	10.0 to 14.5
7	279	11.1 to 16.1

The projected performance and economic results do not account for several factors:

- Although both the HPAC and advanced hybrid systems require regular maintenance, it is critical for correct advanced hybrid system operation, especially in areas with high water mineral content. An unmaintained HPAC unit will probably still provide adequate space conditioning, though at reduced efficiency. Lack of proper maintenance on a hybrid system will ultimately lead to system failure. Both school district maintenance staff and teachers need to be trained on the maintenance needs and operational constraints of the advanced hybrid system.
- The statewide average electric rate used in the analyses represents a blended rate based on energy and demand charges. The advanced hybrid system, with its significant cooling season demand reduction benefit, should generate better savings than those reported here.
- DOE-2 simulation results indicated the advanced hybrid system can maintain indoor air temperatures in each of the 16 California climate zones. In some of the areas with high outdoor wet bulb temperatures, such as Palm Springs and San Diego, the IDEC may fail to keep the indoor conditions dry enough for typical classroom activities (papers begin to stick together above 70% RH).
- A recent survey of portable classrooms found that 68% of teachers were likely to turn off the HVAC system due to noise (CARB 2003). Although this is likely to lower HVAC energy use it will likely also lead to IEQ problems. The hybrid system's low velocity fan provides airflow at a lower noise level and therefore is more likely to be left on, as was found from the monitoring.

[9] These seven zones amount to 84% of the estimated annual RC production volume.

5 Conclusions

Monitored energy savings due to use of the advanced hybrid system in the four monitored classrooms were mixed. Although monitored cooling savings were close to expected levels, daily heating energy use was significantly higher due to operational and control problems. Even though the monitored HPAC heating efficiency was low due to high strip heat use, the advanced hybrid heating use was higher due to continuous operation as a result of commissioning problems.

DOE2 modeling indicated, that if control problems can be overcome, the advanced hybrid system provides an efficient alternative to conventional HPAC systems. In addition to efficient space conditioning (82% kWh savings and 72% summer peak demand reduction), the advanced hybrid system offers continuous high efficiency outdoor air ventilation. Unfortunately, the advanced hybrid technology evaluated here is not currently available as a packaged system, making it more costly in the short-term. If a market develops for the advanced hybrid system technology, competing manufacturers should appear, reducing incremental costs.

Although the advanced hybrid system offers significant energy efficiency benefits, there are still some issues to address. The IDEC system requires more frequent maintenance than a standard HPAC system. Evaporative media needs to be replaced (typically on 3-5 year intervals), and teachers and service personnel need to be trained on the operational characteristics and maintenance requirements of the system. In addition, the IDEC will have difficulty providing thermal comfort in the southern desert regions of California where a combination of elevated humidity and mid-summer temperatures frequently exceeding 110ºF and in year-round schools in inland valley regions.

The low monitored efficiency of the HPAC system demonstrated the need for efficient heating alternatives, but the difficulty and cost of installing gas heating in a relocatable classroom project may be a significant barrier. Other possible heating systems compatible with the IDEC cooling system, such as electric ceiling radiant or an integrated heat pump, should be investigated, although these systems may not be as source-energy efficient as the natural gas solution.

The importance of proper HVAC controls cannot be overemphasized. This single factor was common to both the HPAC and advanced hybrid systems and had the greatest influence on energy use. The energy effects of controls such as ramping thermostats (to prevent strip heat use), lock-out timers, and occupancy sensors should be investigated further.

The advanced hybrid system offers great potential for improving the energy efficiency of relocatable classrooms, while also improving indoor air and environmental quality. A larger scale field test of advanced hybrid systems (with possibly an alternative heating method) would provide more data on system performance, installed costs, and teacher/staff satisfaction.

6 Acknowledgements

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APPENDIX A:

DETAILED FIELD MONITORING RESULTS

This appendix includes more detailed monitoring data on HVAC system performance. Figures A-1 through A-5 present average demand profiles for the four RCs for the more extreme days of the heating and cooling season. The selected days, ranging from nine to 21 days depending upon climate and the operation of the RC on those days, demonstrate what typical mid-winter or mid-summer profiles look like.

Figure A-6 plots HPAC system heating demand as a function of outdoor air temperature. The selected six-minute monitoring points represented full-load operation during the six-minute interval and the surrounding time intervals, to insure 100% operation during the interval. The striking characteristic in this plot is the occurrence of heat pump strip heat across outdoor temperatures. This clearly is the major factor contributing to the low HPAC heating efficiency.

Figure A-7 plots HPAC system cooling demand as a function of outdoor air temperature. Data points were selected in a manner similar to heating. The small number of cooling data points translated into short run cycles, which meant the system was rarely reaching steady state operation. This is reflected in Figure A-8, which demonstrates EERs considerably lower than manufacturer's data would indicate.

Figures A-9 and A-10 plot monitored outdoor dry bulb temperature against NOAA data for the same day from the closest locations and a day from the TMY file with the same average outdoor air temperature. Both study sites show higher morning temperatures due to solar effects, e.g., increased absorbance of the asphalt playground on which the Modesto RCs were sited.

Figure A-1: IDEC Gas Consumption Profile

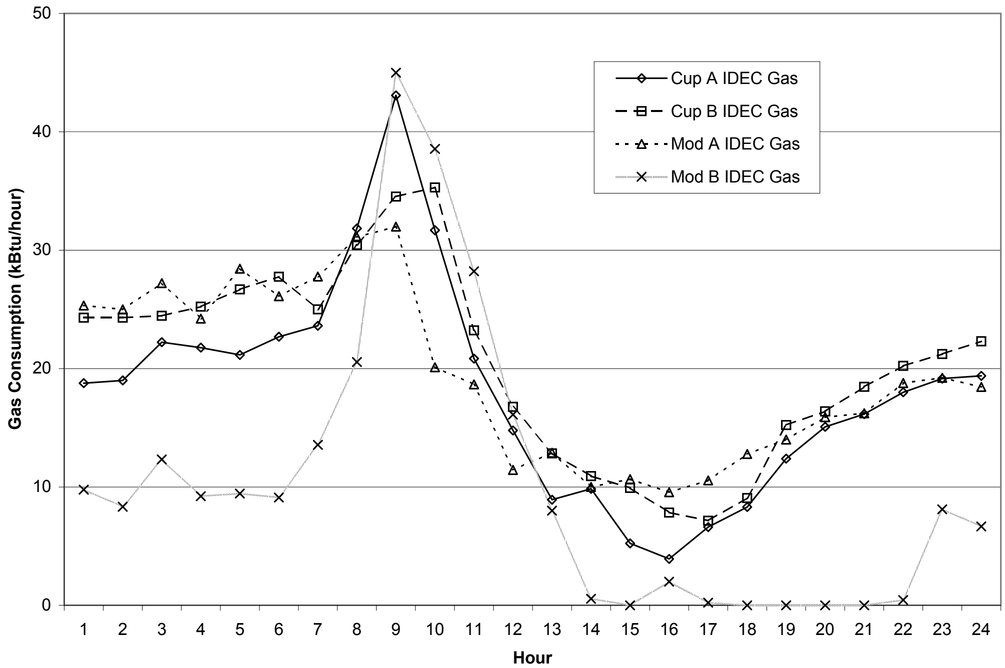


Figure A-2: HPAC Heating Electrical Load Profile

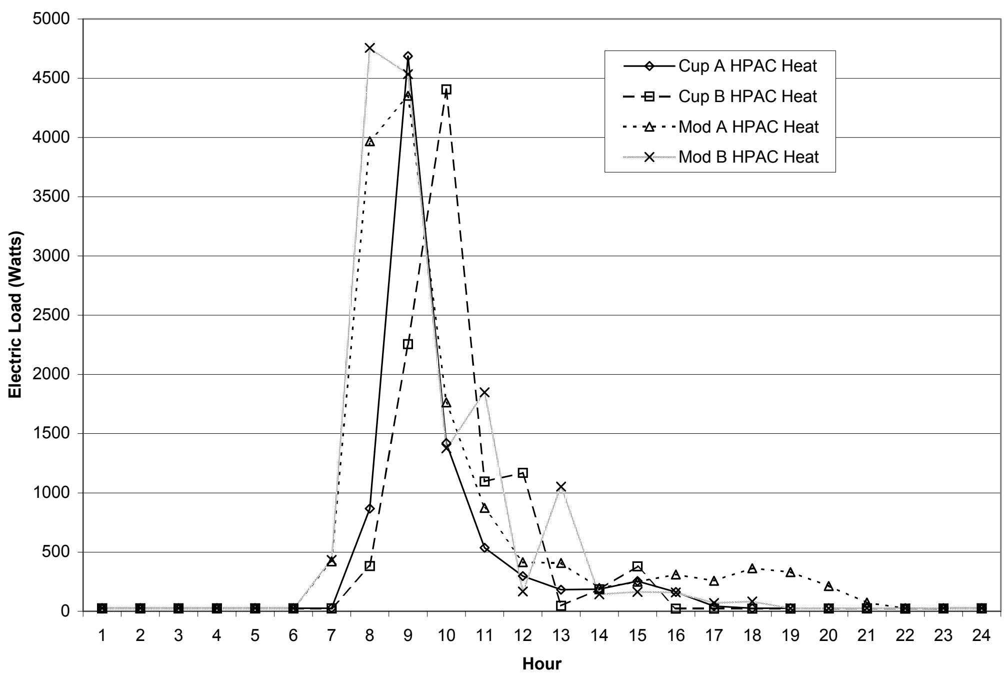


Figure A-3: HPAC Cooling Electrical Load Profile

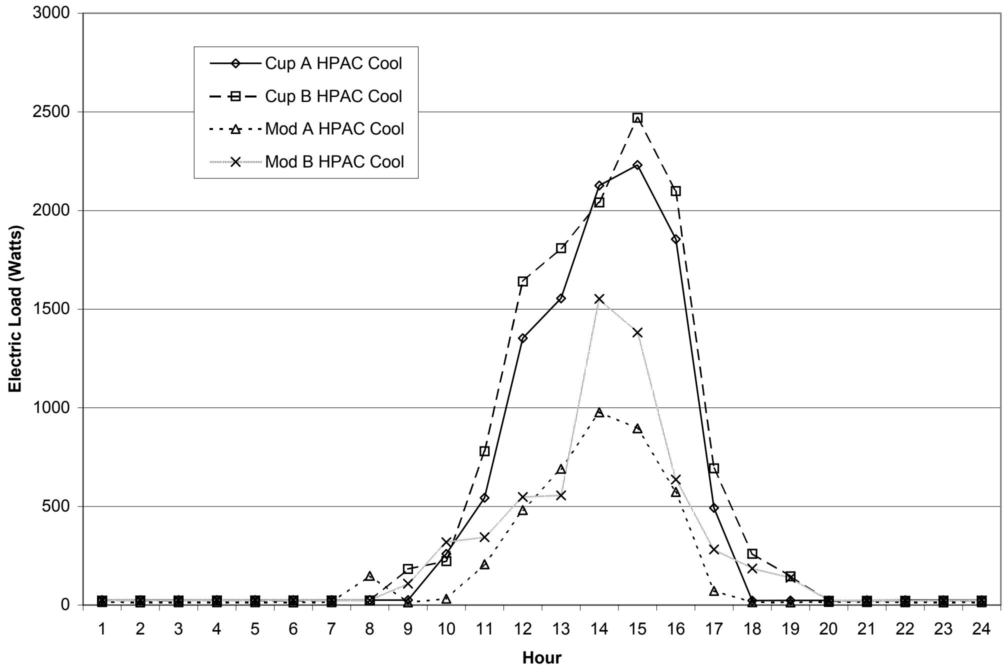


Figure A-4: IDEC Heating Electrical Load Profile

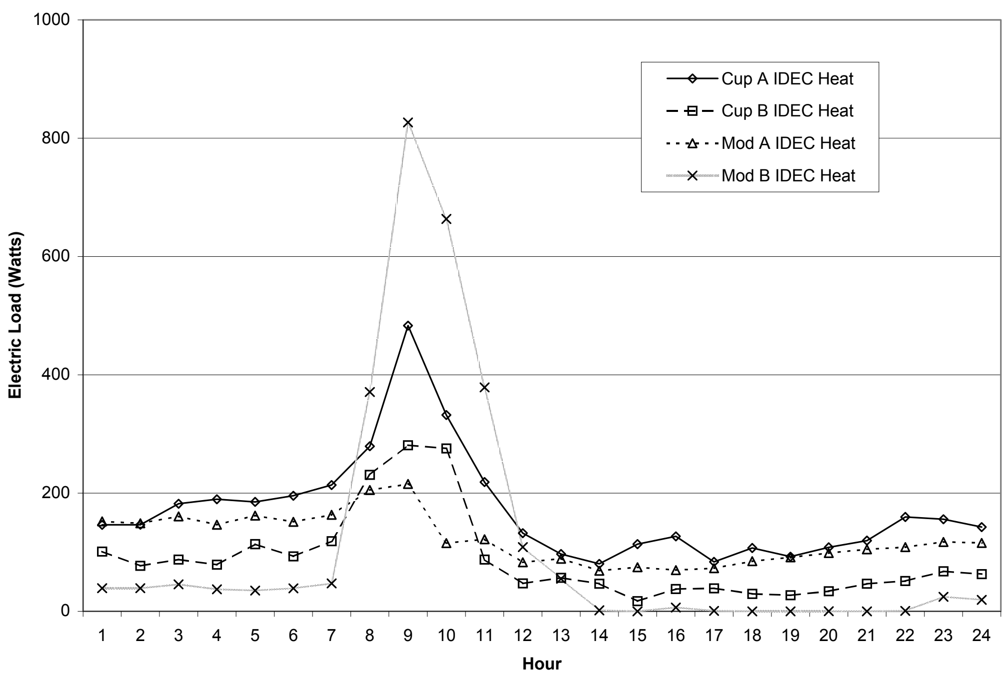


Figure A-5: IDEC Cooling Electrical Load Profile

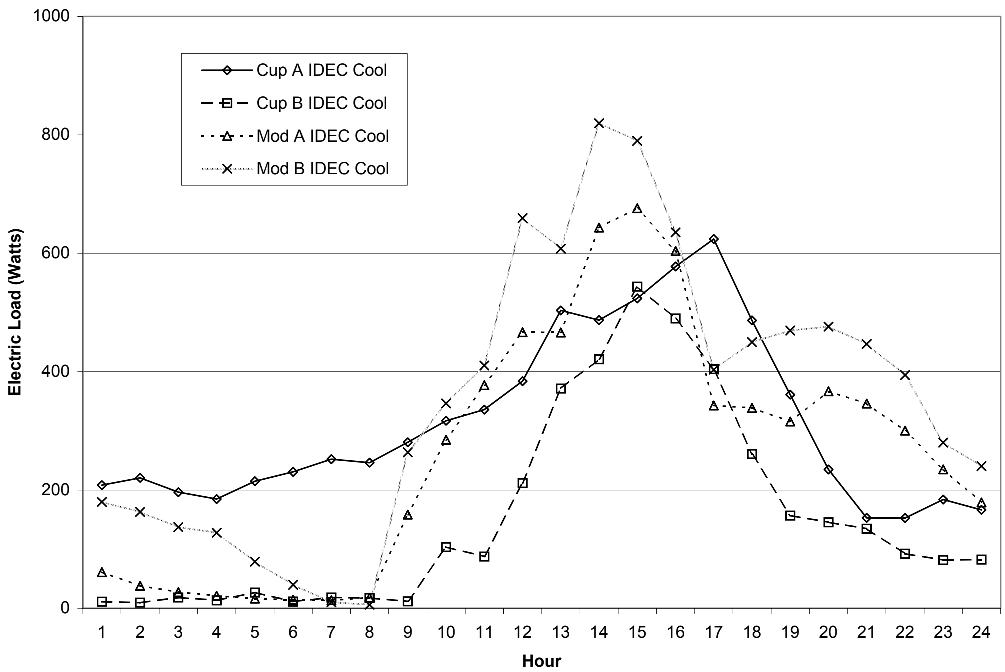


Figure A-6: HPAC Heating Demand (full-load operation)

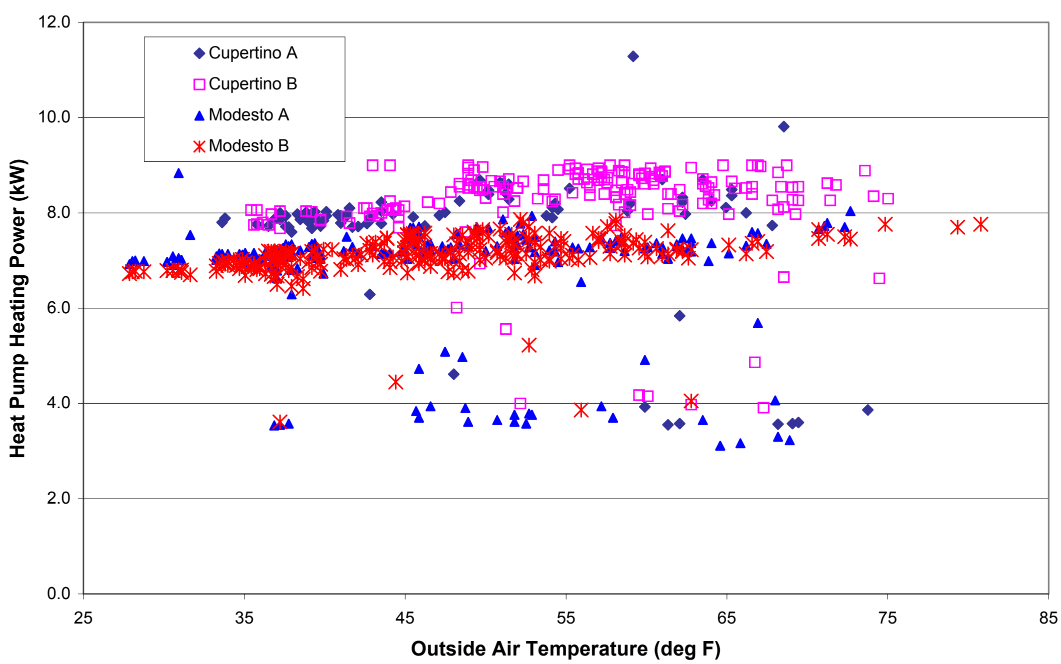


Figure A-7: Monitored HPAC Cooling Demand vs. Outdoor Temperature

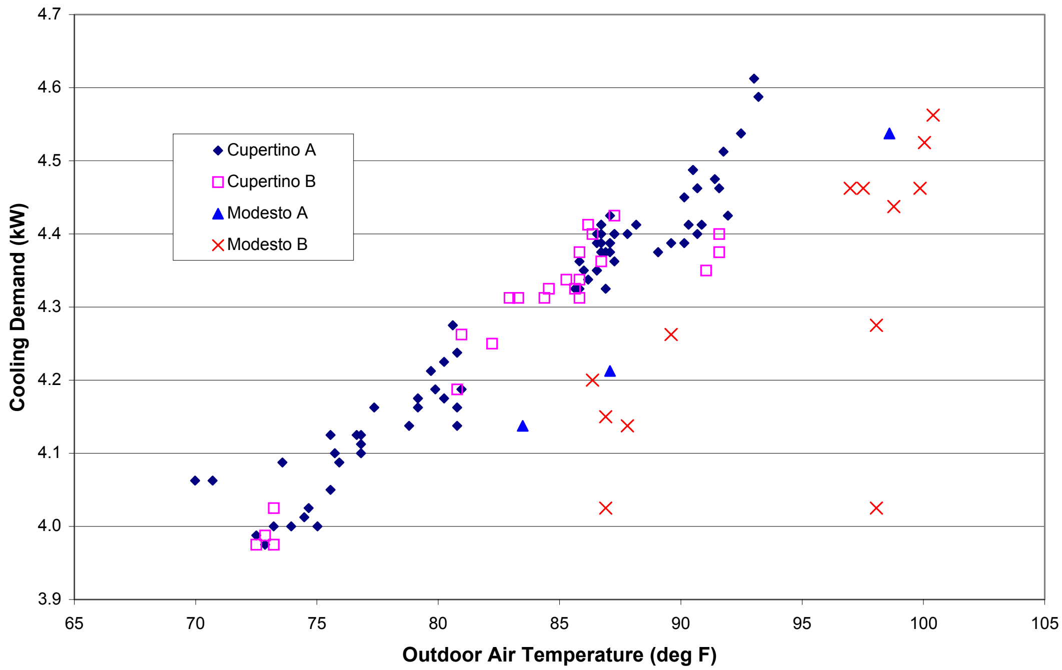


Figure A-8: Monitored HPAC Cooling EER vs. Outdoor Temperature

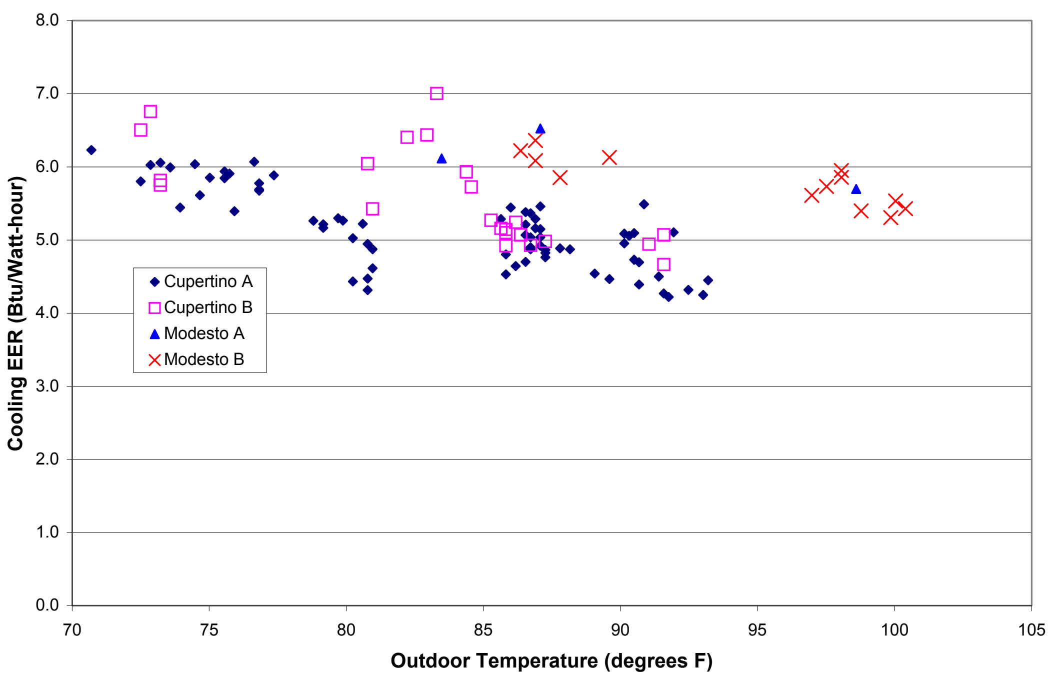


Figure A-9: Weather Data for Cupertino on June 4, 2002

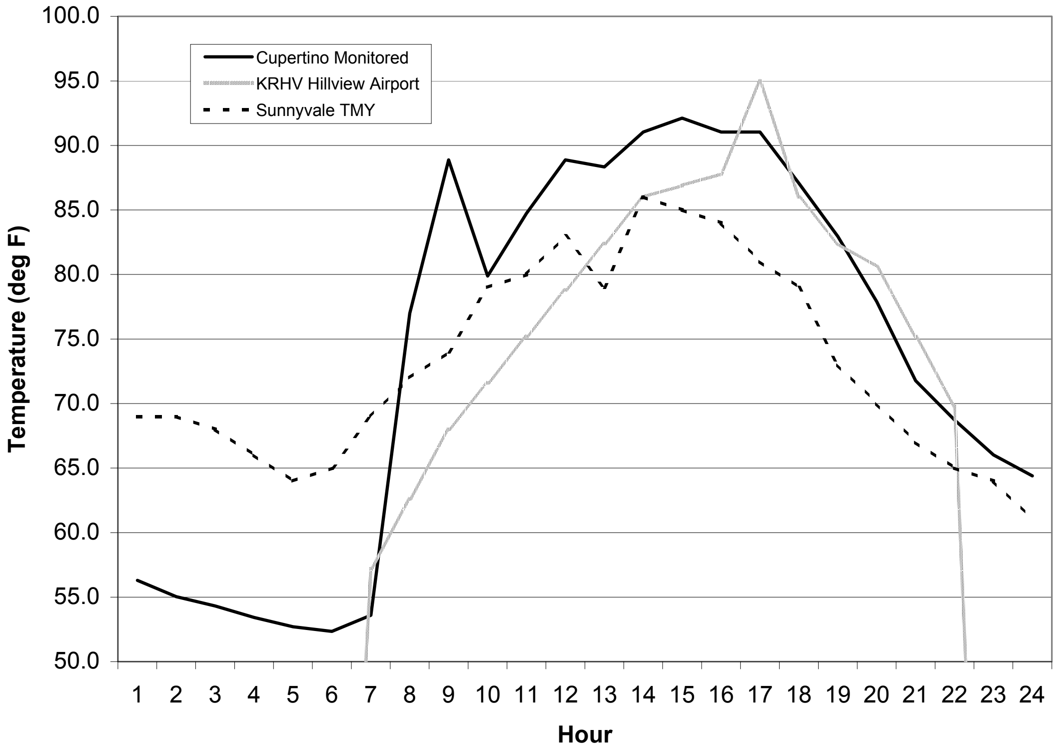
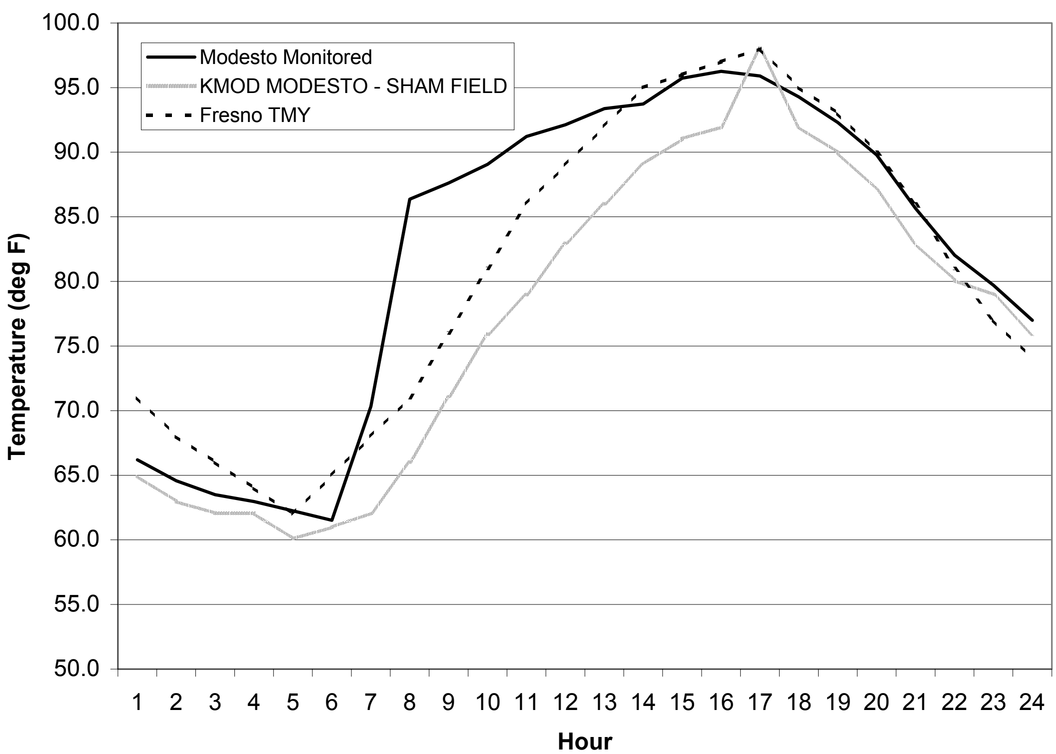


Figure A-10: Weather Data for Modesto on May 29, 2002



APPENDIX B:

DOE-2 SIMULATION RESULTS

			Electric (kWh)				Demand (kW)		Gas (therms)	Total Source	Annual	Savings			
System	CZ	Lights	Heating	Cooling	Fan	Total	Heating	Cooling	Heating	Energy (Mbtu)	Cost	Mbtu	Cost	Mbtu %	Cost %
HPAC	1	861	751	37	913	1701	6.1	3.9	0	17.42	$253				
IDEC	1	861	20	0	62	82	0.2	1.3	37	4.54	$40	12.9	$213	74%	84%
HPAC	2	861	937	285	905	2127	8.6	4.6	0	21.78	$316				
IDEC	2	861	21	10	232	263	0.2	1.3	44	7.09	$72	14.7	$245	67%	77%
HPAC	3	861	519	187	868	1574	4.2	4.4	0	16.12	$234				
IDEC	3	861	15	5	157	177	0.2	1.3	26	4.42	$46	11.7	$188	73%	81%
HPAC	4	861	639	321	881	1841	7.4	4.4	0	18.85	$274				
IDEC	4	861	16	12	222	250	0.2	1.3	32	5.76	$61	13.1	$213	69%	78%
HPAC	5	861	400	266	865	1531	5.9	4.3	0	15.68	$228				
IDEC	5	861	11	10	215	236	0.2	1.3	21	4.52	$51	11.2	$177	71%	78%
HPAC	6	861	246	316	823	1385	4.7	4.4	0	14.18	$206				
IDEC	6	861	8	9	237	254	0.2	1.3	13	3.90	$47	10.3	$159	72%	77%
HPAC	7	861	222	361	828	1411	3.3	4.3	0	14.45	$210				
IDEC	7	861	7	11	259	277	0.2	1.3	11	3.94	$49	10.5	$160	73%	76%
HPAC	8	861	270	517	841	1628	4.8	4.4	0	16.67	$242				
IDEC	8	861	8	18	335	361	0.2	1.3	14	5.09	$64	11.6	$178	69%	74%
HPAC	9	861	340	483	833	1656	5.6	4.6	0	16.96	$246				
IDEC	9	861	10	17	308	335	0.2	1.3	18	5.23	$63	11.73	$183	69%	74%
HPAC	10	861	327	514	853	1694	5.4	4.7	0	17.34	$252				
IDEC	10	861	9	16	314	339	0.2	1.3	17	5.17	$63	12.2	$189	70%	75%
HPAC	11	861	958	400	904	2262	8.9	4.8	0	23.16	$336				
IDEC	11	861	24	12	280	316	0.2	1.3	47	7.94	$82	15.2	$255	66%	76%
HPAC	12	861	833	362	902	2097	7.4	4.7	0	21.47	$312				
IDEC	12	861	22	13	272	307	0.2	1.3	43	7.44	$77	14.03	$234	65%	75%
HPAC	13	861	751	569	881	2201	7.4	4.7	0	22.54	$327				
IDEC	13	861	19	19	354	392	0.2	1.3	37	7.71	$86	14.8	$242	66%	74%
HPAC	14	861	901	514	905	2320	10.3	4.9	0	23.75	$345				
IDEC	14	861	19	14	317	350	0.2	1.3	44	7.99	$85	15.8	$260	66%	75%
HPAC	15	861	193	1207	939	2339	3.6	7.0	0	23.95	$348				
IDEC	15	861	6	32	522	560	0.2	1.3	11	6.83	$91	17.1	$256	71%	74%
HPAC	16	861	2136	117	979	3232	11.0	4.4	0	33.09	$481				
IDEC	16	861	41	4	136	181	0.2	1.3	93	11.15	$96	21.9	$385	66%	80%