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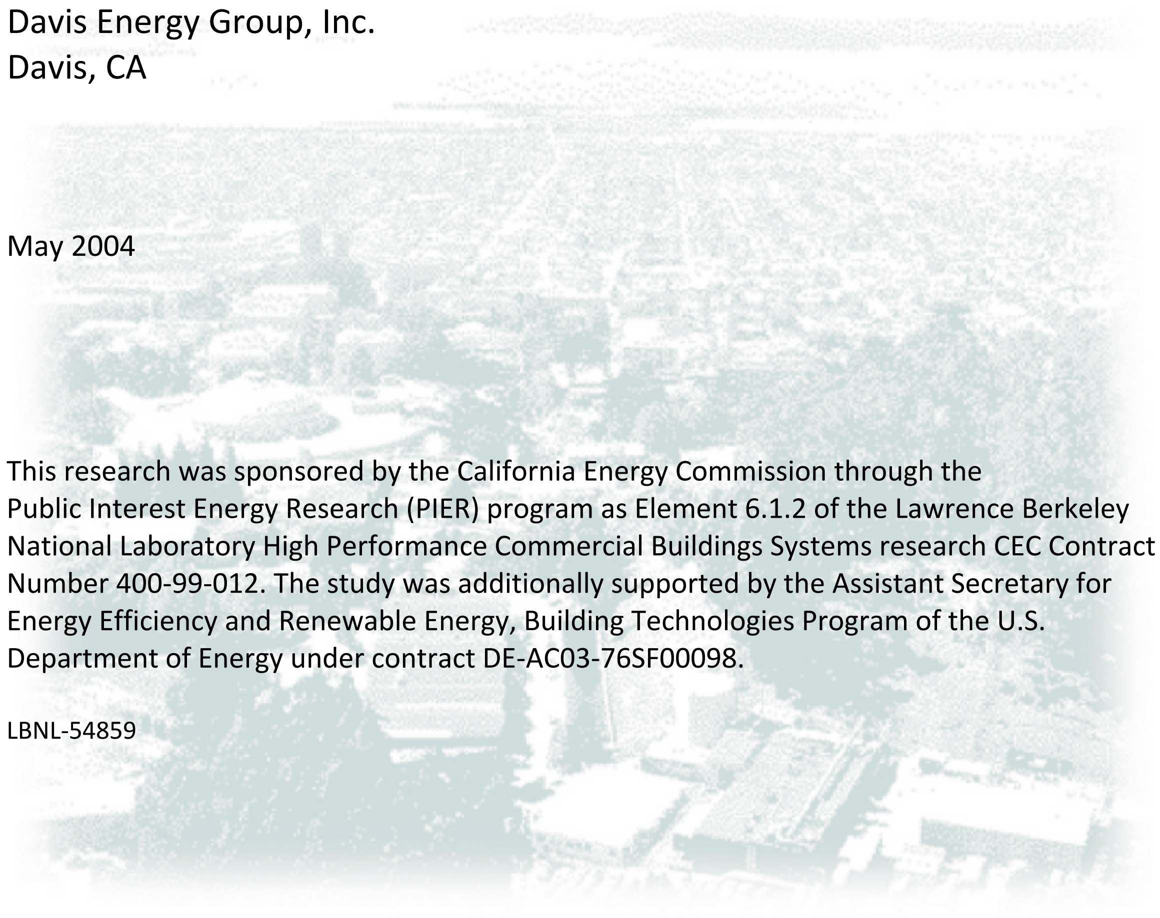

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ABSTRACT

Building design concepts that focus on energy efficiency may conflict with those intended to provide excellent indoor environmental quality (IEQ). Careful selection of a heating, ventilating, and air-conditioning (HVAC) system, and low-emission interior finish materials, can result in win-win designs that minimize tradeoffs between energy and IEQ. We demonstrated energy and IEQ benefits in four new relocatable classrooms (RCs) monitored in two climate regions of California for one year. We used a case-crossover experimental design to compare energy and IEQ characteristics of a hybrid HVAC system that provides continuous ventilation (indirect-direct evaporative cooler with high-efficiency hydronic gas heat) to a standard heat pump system. Additionally, we explored the IEQ benefits of measurement-based selection of interior finish materials with low emissions of health-relevant volatile organic compounds (VOCs) including formaldehyde. Monitored data were used to calibrate DOE-2 models that simulated California-wide energy saving potential of RCs employing energy efficient building components including the hybrid HVAC system. IEQ monitoring results from our field investigation indicated that VOC concentration reductions, typically 50% or more, were achieved through improved ventilation while simultaneously average cooling and heating energy costs were reduced by 50% and 30%, respectively. Incremental annual California-wide energy impacts from installation of hybrid HVAC systems in 4,000 new RCs were projected to be: 5,975 MWh of electricity savings; 23.8 MW winter and 13.1 MW summer peak electric load reduction; 1,025 MBtu natural gas consumption from switch to gas heating; 50,931 MBtu source energy reduction; and a combined school district annual operating cost reduction of $880,900.

Introduction

Energy efficiency and indoor environmental quality (IEQ) are key building design issues, but they are often considered to conflict when design, construction, and operation decisions are made. The issues have become greater as government agencies and the building sector continue to seek improvement in energy efficiency. Designs achieving good IEQ can be expected to have beneficial effects with respect to occupant health, work performance and attendance, therefore promoting their implementation is of benefit to society.

This study was conducted with the goal of quantifying and demonstrating technologies with the potential to simultaneously improve energy efficiency and IEQ in commercial buildings. This study focused on new relocatable (modular or portable) classrooms. Relocatable classrooms (RCs) are particularly well suited for this study because they are self-contained structures with dedicated HVAC systems and well-defined occupancies. Their study is relevant to current building stock issues – for example, an estimated 85,000 RCs are currently in place in California schools, and the numbers have been increasing at a rate of 3000 to 10,000, or more per year since 2001 (CARB/CDHS 2003; EdSource, 1998; Sarich, 2001). The RC manufacturing industry estimated a projected growth rate of 20% per year nationwide for this decade (Lyons, 2001).

Evidence, both anecdotal and data from survey, suggests that HVAC systems in RCs are not operated effectively, with mechanical ventilation frequently underutilized for a number of reasons, including inadequate training in HVAC operation, system noise, energy saving measures, and inadequate maintenance and installation practices (CARB/CDHS 2003; Shendell 2003a). The 6-8 hours spent indoors during the school day dominates student and teacher's school-day air pollutant and noise exposures. IAQ and physical environmental stresses can adversely impact the health of students and teachers.

RC construction is an important factor from both the energy efficiency and IEQ perspectives. The standard RCs sold in California typically just meet the state minimum energy efficiency codes. The high performance RCs that were designed in this study, utilized lower building shell U-values, improved fenestration and lighting, and cool-roof coatings, as well as the energy efficient HVAC system discussed below.

RC construction materials selection is also important from the IEQ perspective. Many materials commonly used in construction can emit volatile organic compounds (VOCs) and aldehydes that either are odorous or pose potential health hazards ranging from respiratory irritation to cancer. Selection of low emitting interior finish materials in RCs can ensure lower concentrations. A component of this study was to test a process for selecting alternate construction materials that have lower emissions of these compounds, and evaluate its benefits.

Methods

The field study phases included school district and RC manufacturer recruitment, RC design specification and construction, RC installation at schools and instrumentation; field measurement and data collection during cooling and heating seasons, and data analysis. The energy analysis phase included use of energy consumption data from the field study to calibrate a DOE2 RC energy simulation model and to use this model to conduct a cost-benefit analysis and energy savings analysis for the advanced RC design across 16 California climate zones. Methods are summarized below and provided in more detail by Shendell et al. 2002 and Rainer et al. 2003.

Study Site Selection and Relocatable Classroom Design

Several school districts and an RC manufacturer were recruited for participation in the study. To test the RC designs in diverse climates, we identified school districts (SDs) in two distinct regions: the CA Central Valley (more extreme climate) and the San Francisco Bay Area (SF) (moderate climate). We secured agreements for placement of two high-performance RCs each at a SF Bay Area elementary school ("SDA," Cupertino) and a Central Valley elementary school ("SDB," Modesto). In this paper we refer to classrooms of type "*A*" (alternate materials included) and "*B*" (standard materials) located in *SDA* and *SDB* as SDA-A, SDA-B, SDB-A, and SDB-B.

The high performance RC (HPRC) design (Table 1) used in this study combines available energy efficient construction materials and methods including additional wall, floor, and ceiling insulation; ceiling vapor barrier; "Cool Roof" reflective roof coating, low-emissivity window glazing; and efficient (T8) fluorescent lighting (DEG, 2000). Each of the four study RCs were equipped with two HVAC systems: a standard 10 SEER heat-pump air conditioning system (HPAC), and an energy-efficient indirect/direct evaporative cooler (IDEC) which is suitable for use where outdoor summertime humidity is moderate to low. The IDEC supplies continuous ventilation at ≥15 CFM (7.5 L s^{-1}) $person^{-1}$, even when heating or cooling is not required. Additionally, compared to the standard heat-pump system, it consumes about 70% less cooling energy. As it has no compressor and a quiet fan, the noise output from the system is lower. Incorporated into the IDEC is an 85% efficient gas-fired hydronic space heating system and an inlet filter system with 65% ASHRAE dust spot efficiency (Apte et al., 2001). The HPAC system incorporates a low efficiency filter that is in the flow path of both supply and recirculated return air. Both the IDEC and the HPAC were set to provide a minimum of 15 CFM of outdoor air, and system controls as currently designed require that the system be turned on in order to provide the required ventilation. In the case of the heat pump system, this action is tied to the temperature set point, so that frequently when no thermal conditioning is needed, no ventilation is provided. The IDEC system supplied room air through three 2 foot square ceiling diffusers evenly spaced across the length of the RC, while the HPAC systems used only two. The HPAC's recirculating air system provides 25% outside air, while the AH provided 100% outside air in a single pass with excess pressure vented from the room via relief dampers on the opposite end of the building. HVAC installation was identical for all four study RCs.

Table 1: HPRC Building Envelope Characteristics

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

To study VOC source reduction potential, SDA-A and SDB-A received alternative low-VOC emitting wall panels, carpet, and ceiling panels (Hodgson et al., 2001, 2002, 2004). Target VOCs considered in the study are toxic air contaminants listed by the state of California and odorous compounds (Hodgson et al., 2001). RCs identified as SDA-B and SDB-B were constructed using the manufacturer's standard materials, otherwise the four RCs were constructed identically. One exception was that Nylon-6,6 broadloom carpet was installed in SDA-B while SDB-B received Nylon-6 broadloom carpet (a source of the VOC caprolactam) due to school district request.

Monitoring and Data Collection

Two HPRCs were sited side-by-side at each of the schools prior to the fall 2001 semester. They were occupied and used by 3rd and 4th grade classes consisting of about 20 and 30 students in SDB and SDA, respectively, and one teacher. During nine weeks of the 2001 fall cooling season and nine weeks of the following heating season, the two RCs at each school were simultaneously operated with either the HPAC or the IDEC unit, alternated weekly. Each RC was instrumented to measure a range of IEQ and energy parameters (Table 2). Indoor and outdoor CO_2 concentrations were measured continuously. The particulate matter (PM) counters measure particle number concentrations in six size ranges from 0.3 to 10 micrometers. Real-time data were stored as 6-minute averages to a central data acquisition system (CDAQS) operated continuously. PM mass concentration was calculated from particle count concentration, based upon bin size diameter and an assumed density of 1 g cc^{-1} (note that if the true density was >1 g cc^{-1} then the calculated concentrations would be an underestimate). During the study period, the RCs were each visited by a technician once a week to retrieve data stored on the CDAQS and collect integrated-schoolday (7-8 hr) indoor and outdoor VOC and aldehyde samples for later analysis. A thermal comfort cart, designed and constructed at LBNL based upon the ASHRAE 55-1992 thermal comfort standard (ASHRAE, 1992), was operated in three locations in each classroom. Observations of HVAC usage and an inventory of cleaning and teaching supplies were also collected (Shendell et al., 2002, 2003b). At the end of the weekly technician visit, the system operation was switched from HPAC to the IDEC, or visa-versa.

Table 2. IEQ and energy monitoring instrumentation in study relocatable classrooms

Parameter	Method[1]	Location[2]
Continuous:		
Carbon Dioxide	NDIR	I, O
Particle size, count	Laser Counter	I,O
Relative Humidity	Capacitance	I, O,HPD, ID, TC, C
Temperature	Thermistor	I, O,HPD, ID, TC, C,
Air Velocity	Thermo-anemometer	TC
Sound Level	dB, A-wtd., Leq	C
Door open	Door sensor	Door
Window position	LDP	
Wind speed, direction	Anemometer	O
Electricity	Current transducer	HVAC, Lights, Total
Natural Gas	Gas meter	IDEC Heating
Time-averaged:		
VOC[3]	Multisorb GC/MS	I, O
Formaldehyde, acetaldehyde[3]	DNPH, HPLC UV detector	I, O
Thermal Comfort[4]	ASHRAE 55-1992	I (0.1m, 0.5m, 1.1m)

[1] NDIR=non-dispersive infrared; multisorb=multisorbent tubes; GCMS=gas chromatography/mass spectrometry; HPLC=high performance liquid chromatography w/UV detection; LDP = linear displacement potentiometer; A-wtd=A-weighted, L_{eq} = equivalent noise level.

[2] I=Indoors, O=Outdoors, HPD=Heat pump system diffuser, ID=IDEC Diffuser, TC=thermal comfort cart, C=Indoors@ 2.5m, center of RC, m=meters above floor.

[3] See Hodgson *et al.,* 2001 [4] See ASHRAE, 1992

Participating teachers and school custodians received training on the operation of the two HVAC systems and were briefed on field visit procedures and the schedule of weekly system switching. In order not to bias the teachers' behavior, we avoided discussing IEQ issues with them and simply described the project as a study to test a new energy-efficient HVAC system. We instructed them to turn the IDEC on at the beginning of the school day as it runs automatically, but to use the HPAC system as they would normally.

Energy Analysis Methods

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. Operational 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, 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 has been satisfied. Finally, door and window use, which affect ventilation, are difficult to define.

With the project's weekly alternating HVAC system operation, data were collected during fairly comparable weather patterns. 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.

DOE2 Modeling. Prior DOE2 modeling utilized assumed thermostat and lighting schedules (DEG 2000). These assumptions were updated based on the monitoring data collected at the SDA and SDB sites to improve the accuracy of savings projections.

The base case model was assumed to meet the revised 2005 California energy 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.

Statewide Projections. Based on California Department of Education data on K-12 enrollment projections by county, we estimated RC placement on a climate zone basis. Figure 1 plots where the projected 4,000 RCs built annually would be installed. The greater Los Angeles area (climate zones 8-10) is projected to account for over half of annual RC installations.

RC simulations of statewide energy demand were completed for each of the 16 climate zones for both HPAC systems (nominal 6.8 HSPF, 12 SEER) and AH systems. Statewide projections were determined by factoring the "per unit" impacts by the projected installations in each climate zone. Operating cost savings were computed based on statewide average commercial electric rate of $0.1487/kWh and an assumed statewide average of $0.74 per therm. Statewide runs were completed to ensure comparable loads and IEQ conditions in both cases. Table 3 summarizes DOE2 inputs for these runs.

Figure 1. Projected Annual RC Installations by California Climate Zone

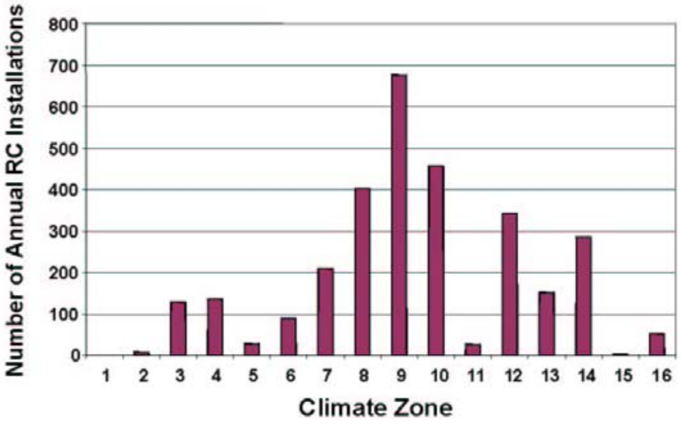

Table 3. DOE2 Inputs for Statewide Simulations

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

Results

Indoor Environmental Monitoring

Measured Carbon Dioxide Concentrations

Table 4 summarizes six-minute average carbon dioxide (CO_2) concentrations in the four RCs stratified into four seasons, and by RC and time period (T.P. see Table footnotes). School hours average ambient CO_2 concentrations, were similar across HVAC system operation weeks each season, i.e., within 5%. The single exception was SDB in the heating season, where the difference between AH system and standard HVAC system (HPAC) operation weeks was approximately 10%. Therefore, across seasons, we assumed background levels of CO_2 did not have a significant influence on measured indoor CO_2 concentrations, i.e., did not confound the comparison of AH system versus HPAC weeks. The results also indicate that, on average, ambient CO_2 concentrations were slightly higher in SDB than in SDA, which was expected due to regional attributes. CO_2 maxima reflect occupied periods when the HVAC systems were not operated.

The maximum six-minute average indoor CO_2 concentrations always exceeded the 1000 ppm level from the ASHRAE 62-1 (2001) minimum ventilation standard equivalent to 15 CFM/occupant (ASHRAE 2001) for all RC and HVAC system combinations. The variation in maximum indoor CO_2 concentrations was in a great part due to the teacher's HVAC operation practices, with the peak values signifying periods when the teachers were not operating the systems.

Table 4. Carbon dioxide concentrations in new relocatable classrooms by time period (T.P.)[1], season, and HVAC[2] system operated.

			Indoors T.P. 1-4	Indoors T.P. 1		Indoors T.P. 2		Indoors T.P. 4		Out T.P. 1-4
SD/RC	**Season**	**HVAC**	**max**	**avg.±std**	**90%**	**avg.±std**	**90%**	**avg.±std**	**90%**	**avg**
SDA-A	Cooling	AH	2610	670±330	1040	820±450	1180	550±230	750	390
		HPAC	2850	820±440	1410	1090±460	1620	790±340	1270	370
	Heating	AH	2000	630±240	1000	740±270	1010	660±210	970	400
		HPAC	2680	930±550	1860	1420±600	2300	1140±520	1850	410
SDA-B	Cooling	AH	2860	790±460	1420	990±540	1730	700±290	1000	390
		HPAC	2870	880±530	1730	1230±570	2110	870±420	1430	370
	Heating	AH	1690	640±270	1030	690±250	1030	760±230	1060	400
		HPAC	2790	760±420	1290	1280±650	2260	1190±580	2070	410
SDB-A	Cooling	AH	3090	790±370	1270	1070±620	2080	930±620	1860	400
		HPAC	2770	850±450	1360	1100±500	1810	880±290	1260	400
	Heating	AH	2670	720±320	1110	960±480	1270	760±380	960	400
		HPAC	2580	970±410	1550	1660±220	2000	1650±500	2160	450
SDB-B	Cooling	AH	3090	650±260	910	850±480	1640	700±470	1270	400
		HPAC	2100	660±280	1020	800±360	1420	970±360	1420	400
	Heating	AH	2600	580±220	700	1000±520	1780	1240±630	2220	400
		HPAC	3140	1040±460	1750	1740±370	2170	1840±560	2500	450

[1] T.P. 1=AM before recess; T.P. 2. = AM before lunch; T.P.4 = post lunch until end of school day

[2] AH denotes the Advanced Hybrid and HPAC denotes the standard heat pump HVAC systems.

Cooling demand during cooling season was assumed to be greater in the afternoon (T.P. 4). Mean T.P. 4 indoor CO_2 concentrations in this season across SDs and RCs were lower during AH system operation weeks than during HPAC operation weeks. The exception to this was SDB-A in the cooling season, likely because this classroom's teacher often opened windows and door rather than use the HVAC during this period.

HVAC operation during the winter 2002 heating season was assumed to be greater in the mornings (T.P. 1 and 2), and greatest in T.P. 1. Mean measured indoor CO_2 concentrations in these seasons in T.P. 1 across SDs and RCs were lower during AH system operation weeks than during HPAC operation weeks. The mean and 90th percentile indoor CO_2 concentrations differed up to a factor of two.

Measured VOC and Formaldehyde Concentrations

VOC and aldehyde data were collected from RCs with both standard and alternative interior finish materials. Target VOCs were selected based on species identified as potentially being emitted from RC materials or were listed as toxic air contaminants under federal Title 3 of the Clean Air Act Amendments of 1990 or California Proposition 65. Published non-regulatory guidelines for indoor environments and ambient air (CARB, 1991, 2001; OEHHA, 2000, 2001a&b), and odor thresholds (Devos *et al.,* 1990), may be used for comparison with our data. See also Table 4 of Hodgson *et al.* (2001).

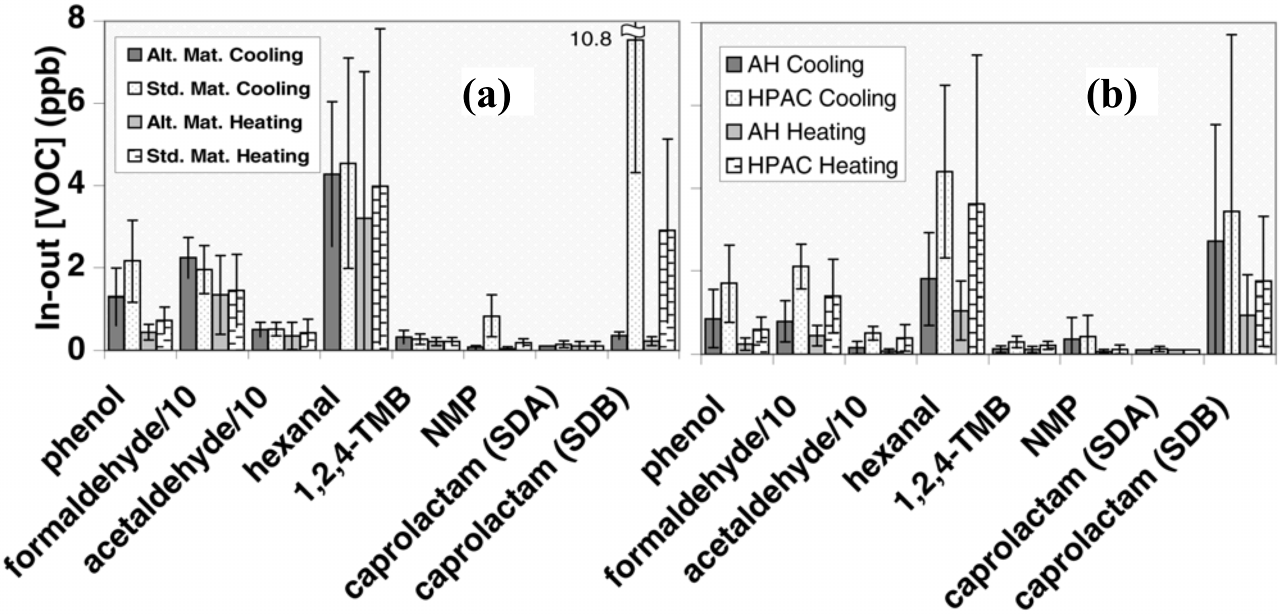

Figure 3. Selected toxic or odorous volatile organic compounds plotted as a function of standard vs. alternate materials RCs during HPAC weeks (a) or between HVAC systems (b) in both cooling and heating seasons. Note NMP = 1-methyl-2-pyrrolidinone; 1,2,4-TMB = 1,2,4-trimethylbenzene, formaldehyde and acetaldehyde values are divided by 10 for scaling. Caprolactam concentrations are separated by SD due to different carpet choices for the alternate material RCs (SDB-B received nylon 6 broadloom carpet).

Figure 3a describes measured concentrations of the selected group of target VOC compounds across seasons, SD, for RCs with standard and alternate materials. Mean concentrations of these compounds linked primarily to interior finish materials were lower in the heating season than in the cooling season. Emissions of compounds from materials generally decreased with time. Slightly lower phenol and 1-methyl-2-pyrrolidinone concentrations in source-modified RCs were attributed to the alternate wall panel, with the trade-off of a contribution to measured but low toluene concentrations (Hodgson et al., 2004). In the cooling season, the alternate wall panels may have led to slightly lower CH_3CHO concentrations as well (also see Shendell, 2003; Hodgson et al., 2004). Across SDs and RCs in the cooling season, mean concentrations of phenol, hexanal, and toluene were lower during AH HVAC system operation weeks than during standard HPAC system operation weeks. The difference between caprolactam concentrations in the source-modified RCs is due to the nylon 6 carpet used in SD-B.

Figure 3b describes measured concentrations of the selected VOC compounds across seasons, SDs, HVAC operating conditions. The figure clearly depicts the marked reductions (Student's t-test, $p<0.05$, see Shendell 2003 and Apte et. al 2004) in average VOC concentrations during AH system weeks relative to HPAC system weeks. These results show the vital role ventilation performs in lowering indoor concentrations of VOCs and improving IEQ.

Across SD, mean and maximum HCHO concentrations did not exceed the CARB (1991) indoor air guideline of~60 $\mu g\ m^{-3}$ (50 ppb). The maximum measured concentrations in the cooling season in SDA during standard HPAC operation weeks, and in SDB across HVAC systems, were near or exceeded the relevant eight-hour CalEPA/OEHHA acute non-cancer reference exposure level (REL) of 33 $\mu g\ m^{-3}$ (27 ppb). In the heating season, only the maximum values in SDB RCs, which were during HPAC operation weeks, exceeded the acute non-cancer REL. In SDA, measured concentrations in the cooling season were higher in SDA-B (standard materials) than in SDA-A (alternative materials), but were slightly higher in SDA-A than in SDA-B during the heating season. In SDB, across seasons, measured concentrations in SDB-A were higher than in SDB-B, though in the heating season the mean was only slightly higher and the SDB-B median was greater than the SDB-A median. Concentrations across seasons, SD and RCs were higher during HPAC operation weeks.

That heating season data did not support the study hypothesis that alternative interior finish materials should lead to lower measured indoor HCHO concentrations than standard materials, was likely due to sources introduced into the classroom by the occupants after the school year had begun. In SDB-A, the class had been provided with student dry-erase boards with exposed particleboard backing. In the cooling season, the mean concentration of HCHO in SDB-A was significantly higher than in SDB-B, contrary to initial expectations supporting this interpretation of the observations. In SDA-A, student art projects completed at home and displayed in the RCs over the second month of the heating season appeared to be constructed of special art materials and adhesives possibly containing HCHO.

In summary, across RCs, measured indoor and indoor minus outdoor HCHO concentrations were higher during HPAC operation, and values in SDB exceeded those in SDA in part due to higher outdoor background concentrations, especially in the cooling season. Variation in HVAC operation behaviors and introduced sources were also influences. The cooling season measurement ranges were similar for AH system operation weeks, and maximum values during HPAC operation weeks were the highest observed. Mean differences in indoor-outdoor HCHO concentrations were not significant by or across seasons and SD with respect to selection of interior finish materials. By or across RCs, however, at the 90% confidence level there were significant decreases in the mean HCHO concentrations over time supporting the assertion that emissions of compounds from RC interior finish materials declined with age and ventilation. Finally, by and across seasons and SDs mean HCHO concentrations in HPAC operation weeks exceeded AH weeks significantly.

Measured Particle Concentrations in Study RCs

Indoor PM concentrations were generally higher than outdoors indicating that the occupant activities were a source of particles. Average cooling season indoor PM10 (combined 0.3 to 10 µm size bins) concentrations were about 45 µg m^{-3} in each RC during HPAC weeks, while they ranged from about 45 to 145 µg m^{-3} during AH weeks. Comparing across HVAC systems within individual RCs, AH week average PM10 concentrations ranged from 4% to 220% higher than those during HPAC weeks. Indoor PM10 concentrations were lower on average during HPAC operation across the size distribution, but they occasionally reached high levels in both HVAC modes. During cooling weeks, the HPAC's recirculation of air through a low efficiency filter may have been more effective than the 65% efficient single-pass filtration of the IDEC. During the heating season average indoor PM10 concentrations ranged from about 20 to 70 µg m^{-3} during HPAC weeks, while they ranged from about 10 to 20 µg m^{-3} during AH weeks. During the heating season, the IDEC operation weeks had 32% to 71% lower average indoor PM10 concentrations. Overall, the indoor PM concentrations were much lower during the heating season.

Measured Noise Levels in Study RCs

A number of existing guidelines have been promulgated for noise levels in school environments with exposures ranging from a time-weighted average sound level, or sound exposure (L_{eq}), of 35 dB(A) to 65 dB(A), with a high of short intervals at levels as high as 115 dB(A) in vocational and music areas (Apte et al. 2004). Children, in their formative years of academic development, require better acoustic quality than adults in classrooms, especially given good speech recognition is necessary for optimal comprehension and learning during the processes of language and reading acquisition (WHO, 2001a-b). Children with hearing impairments and learning disorders are especially susceptible to noise.

Table 5 summarizes measured noise levels as Leq, or time-weighted average exposure. The measured school day L_{eq} (T.P. 1-4) across RCs and seasons in SDA was slightly higher during AH system operation weeks than during HPAC operation weeks. In SDB-A, however, the school day L_{eq} across seasons was similar across HVAC systems, and in SDB-B the school day L_{eq} across seasons was slightly higher during HPAC operation weeks than during AH system operation weeks.

Table 5. AM, PM and day-long summary of classroom noise levels (dB(A)).

		RC A				**RC B**			
	HVAC system operational:	HPAC		Advanced Hybrid		HPAC		Advanced Hybrid	
SD	**Statistic/time period[2]**	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**	**Heating**	**Cooling**	**Heating**
A	school day L_{eq}[1] (T.P.1-4)	58.4	58.6	59.1	59.6	53.7	55.3	54.3	55.9
	school day AM L_{eq} (T.P.1-2)	58.9	**59.7**	59.6	**59.2**	53.2	**55.3**	53.7	**55.0**
	school day PM L_{eq} (T.P.4)	**60.5**	57.9	**60.0**	61.4	**57.5**	57.1	**57.5**	58.7
B	school day Leq (T.P.1-4)	53.5	54.4	53.7	54.3	56.3	55.5	55.9	53.9
	school day AM Leq (T.P.1-2)	53.8	**55.6**	55.3	**55.1**	56	**56.7**	56.4	**54.6**
	school day PM Leq (T.P.4)	**55.2**	54.7	**53.7**	55.2	**58.2**	56	**56.9**	54.9

[1] L_{eq} = time-weighted average sound level, or sound exposure.

[2] T.P. 1=AM before recess; T.P. 2. = AM before lunch; T.P.4 = post lunch until end of school day

Cooling demand during the cooling season was assumed to be greater in the afternoon (T.P. 4). Across SDs and RCs, the school day afternoon L_{eq} in the cooling season was slightly higher during HPAC operation weeks than during AH system operation weeks; the difference in SDB was 1.5 dB(A). Likewise, heating demand during heating season was assumed to be greater in the mornings (T.P. 1 and 2), and greatest in T.P. 1. Across SDs and RCs, the school day AM L_{eq} in the heating season was slightly higher during HPAC operation weeks than during AH system operation weeks. In both seasons these data suggest that occupants were the dominant source of noise, and that the AH system was slightly quieter for conditioning than the HPAC system.

Measurements in SDA-B when the HPAC was operated outside school hours by a teacher working alone in the evening or on a weekend, contributed up to 15 dB(A) above the background noise level. The range observed during the study was approximately 8-15 dB(A). When the HPAC operated in the adjacent RC (SDA-A), the noise level apparently increased about 1-1.5 dB(A); the RC door and windows were closed. During periods when the AH system started up automatically overnight when the thermostat dropped below 55ºF, noise levels appeared to increase approximately 4-7dB(A), only about 50% the noise contributed by the HPAC above background during unoccupied hours. Anecdotally, the teachers all stated that the AH system was quieter in operation that the HPAC, making it easier to teach. For more details of sound data see Apte et al., 2004. Clearly, the levels of noise observed in these classrooms are in excess of acceptable limits for educational environments, however the HVAC systems were only partial contributors.

Thermal Comfort Assessment

Table 6 presents representative cooling and heating season results of the thermal comfort assessment from SDA-A and SDB-A. Data from all four RCs is provided in Apte et al., 2004. Acceptable ranges of operative temperature and relative humidity (RH) for the cooling season, based on ASHRAE Standard 55, are 22.5ºC to 26.0ºC and 30% to 60% RH, respectively. Likewise for the heating season the acceptable ranges were 20.0ºC to 23.5ºC and 30% to 60% RH, respectively (ASHRAE 1992, 1995a).

Cooling Season. In SDA-A across HVAC systems, the acceptable range of thermal comfort was not always achieved, especially at the start of the school day (T.P.1) as well as in the afternoon when the HPACs were not used continuously. This was likely due to a higher measured indoor air RH, driven by ambient conditions and/or a lower ventilation rate, which increased occupant influence on RH. In SDB-A, a higher percentage of the measurements was within the acceptable range of thermal comfort during HPAC operation weeks, although the values in the afternoon were similar across HVAC systems. In SDB-B a higher percentage of the measurements was within the acceptable range of thermal comfort during HPAC operation weeks. These results more likely reflected ambient conditions given each teacher's use of the door and windows. Comparing RCs across HVAC systems, a relatively higher percentage of the measurements were within the acceptable range of thermal comfort in SDB-A than in SDB-B. This was likely because the SDB-A teacher depended on the air conditioning for cooling, while the SDB-B teacher preferred to use the door and windows for ventilation. Across RCs, when ASHRAE Standard 55 was not met, the likely cause was a lower indoor air temperature.

In SDA, average indoor RH levels were slightly higher during HPAC weeks than equivalent AH weeks, while average afternoon RH levels were higher during AH weeks. In SDB, although average indoor RH was lower than SDA, and with a somewhat larger cooling demand, both morning and afternoon average indoor RH levels were slightly higher during AH weeks. Water vapor from the IDEC's direct stage may be responsible for these slight increases in humidity during cooling, however it doesn't appear that this significantly impacted thermal comfort.

Table 6. Summary AM and PM thermal comfort assessment in selected study classrooms per ASHRAE Standard 55 (1992, 1995 addendum).

SD	Season	HVAC System Operational	RC	Time Period During School Hours[1]	Operative T and RH Acceptable[2] (% of time)	Operative T, RH, Air Velocity Acceptable (% of time)[3]	Average Indoor Air T[4] (ºC)	Average Indoor Air RH[4] (%)	# Weeks of Data in Season
A	Cool	HPAC	A	T.P.2	19.4	13.9	20.7	62.6	3
				T.P.4	16.7	15	20.6	61.2	
		AH	A	T.P.2	44.1	9.6	22.1	56.6	4
				T.P.4	24.2	0	21.1	65	
B	Cool	HPAC	A	T.P.2	83.3	28.2	23.8	50.5	3
				T.P.4	53.7	50	24.3	48.4	
		AH	A	T.P.2	50	25	22.5	51.6	4
				T.P.4	52.8	43.4	22.9	53.9	
A	Heat	HPAC	A	T.P.2	46.2		19.6	47.9	4
				T.P.4	61.3	-	20.4	43.4	
		AH	A	T.P.2	79.3		21	39	4
				T.P.4	36	-	19.4	45.6	
B	Heat	HPAC	A	T.P.2	88.9		21.6	48.1	4
				T.P.4	83.4	-	21.5	46.7	
		AH	A	T.P.2	100		21.3	43.2	5
				T.P.4	94.7	-	21.4	41.1	

[1] T.P.2 = AM recess until lunch; T.P.4 = Afternoon until end of school day. [2] operative T and RH within ASHRAE Standard 55 acceptable range (10% dissatisfaction criterion). [3] operative T (offset, if air velocity > 0.2 m/s) and RH within ASHRAE Standard 55 acceptable range (10% dissatisfaction criterion) (% of time). [4] average of temperature (T) measurements, in degrees Celsius (ºC), or of % relative humidity (RH) measurements, at three heights on thermal comfort cart-- 0.1 m., 0.6 m., 1.1 m.

Across SD, RCs, HVAC systems, and time periods, measured air velocities >0.2 m s^{-1} affected the percentage of the measurements within the acceptable range of thermal comfort. Data also suggested that the air velocities were influenced by the HVAC system in operation, the activities of occupants, and ambient influences through open doors and, to a lesser degree, open windows. In general, field measurements in the afternoon in the cooling season were more often within the acceptable range of thermal comfort in SDB than in SDA, likely due to relatively lower measured indoor air RH and/or relatively higher measured indoor air temperature.

Heating Season. In the SDA RCs, in the late morning the percentage of the measurements within the acceptable range of thermal comfort was relatively higher during AH system operation weeks in SDA-A, and in SDA-A than in SDA-B across HVAC systems. During the early morning (T.P.1), thermal comfort in SDA-A was less acceptable during AH system operation weeks than during HPAC operation weeks, perhaps due to slower thermal pickup of the AH system's hydronic heating loop. Across RCs, thermal comfort data suggested that the HPAC was more acceptable in the afternoon T.P., which was when heating demand was usually lowest. During post-recess and T.P. 2 in SDA-A across HVAC systems and in SDA-B during HPAC operation weeks, a relatively higher percentage of measurements were within the acceptable range of thermal comfort, likely driven by several factors. These included increasingly warmer and drier ambient conditions; higher occupant post-recess metabolic rates; and, continued use of HVAC systems for heat and ventilation after the colder, more humid overnight.

Across SDs, RCs, and HVAC systems, when the ASHRAE Standard 55 definition of thermal comfort was not met, likely reasons were lower measured indoor air temperature, especially in T.P.1, and/or the influence of higher ambient RH, e.g., rain. Acceptable thermal comfort conditions were more often met in SDB than in SDA, likely due to greater HVAC use, especially the AH system, and different ambient conditions, especially in the afternoon.

Energy Monitoring, Simulation and Cost Benefits

Full details of energy monitoring simulation, and cost benefit analyses are presented in Rainer et al. (2003). Figures 4a and 4b present monitored daily RC heating season and cooling season electrical energy consumption as a function of average daily outdoor temperature. Gas consumption for the AH is not shown, however Table 7 presents the regression coefficients for both electrical and gas consumption across SD, RC, and season. Figure 5 presents daily cooling and heating season load profiles for the two HVAC systems. DOE2 simulations, calibrated with these HVAC energy consumption data, predict energy consumption and potential savings from using the AH system as compared to the HPAC system.

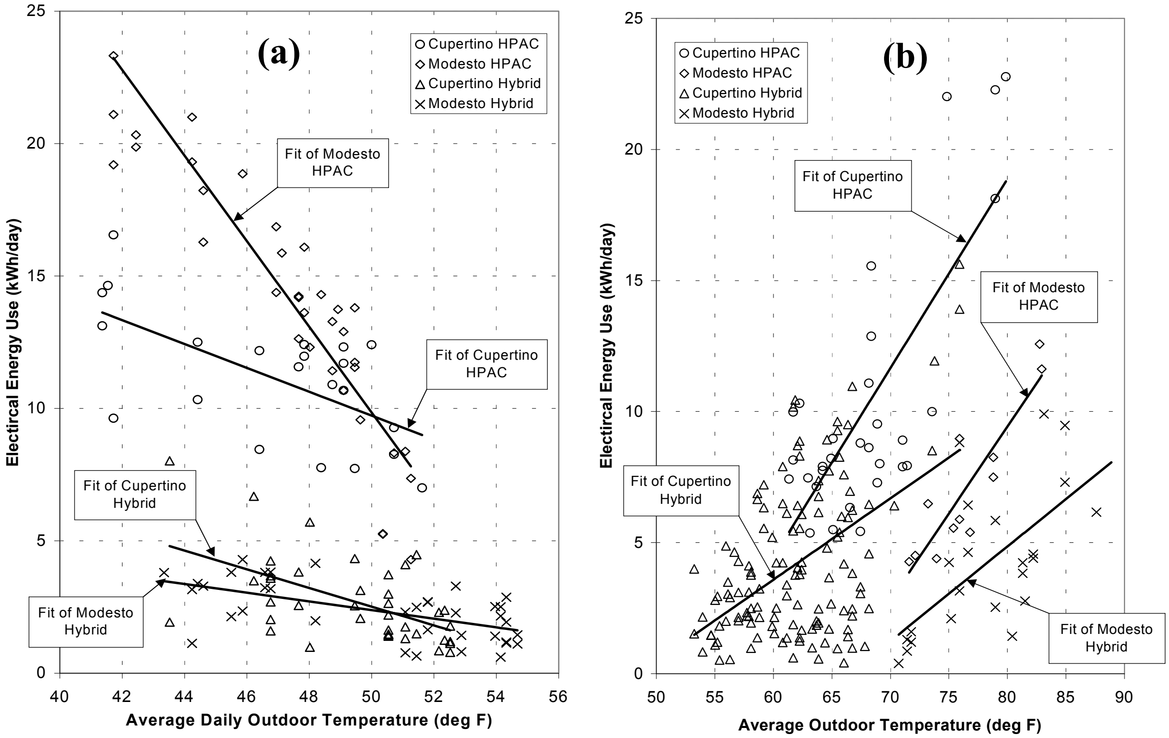

Figure 4. Monitored Daily RC Heating season (a) and cooling season (b) electrical energy consumption in study RCs vs. average daily outdoor temperature.

Table 8 summarizes projected annual energy performance for the two system types in three climate zones: mild San Francisco Bay area (3), warm inland Southern California (9), and hot inland valley, e.g., Modesto (12). AH system heating and cooling energy represents pump and controls energy only; fan energy represents blower operation. AH system electricity savings in these three zones were significant, exceeding 80%. DOE2 projected cooling demand savings exceeded 70% in these three climate zones.

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 1. Statewide projected impacts on source energy and operating cost savings were greater than 80% and demand reductions exceeded 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 due to switch from electric to gas heating; 13 MBtu source energy savings (69% reduction); and a $220 annual operating cost savings, ranging from $159 to $385 (82% reduction). Incremental cost estimates for the AH system range from $1,786 to $2,586 per unit, potentially dropping if production volume were to increase. However, at many school sites, provision of gas to portables may be costly and impractical since its distribution is often not built into school site infrastructures. Based on average AH system incremental costs, an average simple payback of 10.6 years is projected for the more populous climate zones in California.

Table 7. Summary of Energy Use Regressions for HPAC and Advanced Hybrid (AH) HVAC systems: Cupertino (SDA) and Modesto (SDB) RCs.

System/ Season	Constant	T_{in} Coef	T_{out} Coef	R^2	# points
HPAC		**SDA**			
Heating	32.3	-0.451		39%	21
Cooling	-38.9	0.722		58%	29
AH					
Heating	20.2	-0.353		30%	38
Cooling	-15.1	0.311		23%	125
Gas Use	3.4	-0.271	0.215	66%	154
HPAC		**SDB**			
Heating	90.7	-1.617		84%	35
Cooling	-43.6	0.663		80%	11
AH					
Heating	10.6	-0.164		35%	36
Cooling	-24.0	0.361		41%	22
Gas Use	-0.52	-0.149	0.158	90%	76

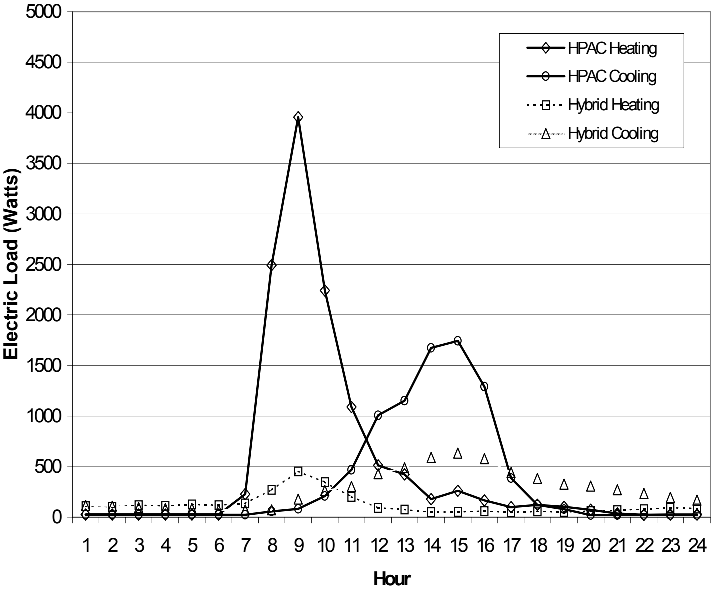

Figure 5. Average HPAC and Advanced Hybrid Hourly Demand Profiles

Table 8: Annual HVAC Energy Use and Demand Projections [1]

System Type	CZ	Annual kWh Heating	Annual kWh Cooling	Annual kWh Fan	Annual kWh Total	Peak kW Heating	Peak kW Cooling	Gas Use 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

[1] 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.

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

System Type	**Electric** Use (MWh)	Gas Use (MBtu)	**Peak Demand** Heating (MW)	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

Discussion and Conclusions

Measured concentrations of HCHO and VOCs support the conclusion that adequate or even improved ventilation were important for good IEQ. Ventilation was more important to the enhancement of IEQ than building material and furnishing source control. Nevertheless, introduction of new materials with high VOC content, e.g., art projects, (for teaching and other purposes) influenced measured concentrations indoors and added uncertainty and variability to these school IEQ studies.

Measured indoor minus outdoor CO_2 concentrations clearly showed a benefit derived from the AH system's continuous ventilation. Average indoor CO_2 concentrations were typically several hundred ppm higher during the HPAC operation weeks. However it is important to point out that teacher preferences played a large role in determining the extent to which ventilation was provided, and HVAC systems were often not turned on for large parts of the school day, leading to higher than desired CO_2 concentrations, and often exceeding the ASHRAE standard of 1000 ppm.

HVAC systems and occupants were the dominant sources of noise exposure for the RCs indoor environment. Mean observed classroom noise levels for several time periods, as well as school-day and school-morning L_{eq} values, exceeded current school district, state, and international guidelines. The monitoring data suggest that the AH system contributed less noise (4-8 dB(A)) than the standard system (10-15 dB(A)) to background levels. Teachers in this study anecdotally stated that the HPAC system was a major distraction to teaching due to noise, and that the AH system was less distracting, however we did not identify the exact causes of these problems. Improved methods should be developed to assess student noise exposure and to identify the causes of the noise distraction described by teachers.

Across SD and RCs, indoor temperature and relative humidity were influenced by several factors. These included afternoon cooling and morning heating demands on HVAC system operation; attributes of the HVAC system technologies; occupants; ambient conditions; and, teacher thermostat set point preferences. In this study, there was negligible vertical thermal stratification when HVAC systems operated, but the majority of the time the ASHRAE Standard 55 for thermal comfort was not met due to high indoor RH.

One surprise in this study was the behavior of the particle filtration components of the two HVAC systems. By adding 65% ASHRAE dust spot efficiency filtration of outside air, the design of the AH system was expected to not only reduce particulate matter from outdoors, but also ventilate the particles generated in the classroom. In contrast, it was expected that the low-efficiency of the HPAC system filters would provide relatively less reduction in indoor particle concentrations. Our findings were that in general the classes were large sources of re-suspended super-micron sized indoor particles that could not be effectively removed by ventilation, but was relatively better removed by the recirculating airflow of the HPAC system. Neither system provided effective particle removal in the classroom.

The improved energy efficiency demonstrated by the AH system, and the potential for reasonable payback on investment in such systems indicates that they have a potential to be accepted into the market. Statewide conservative estimates of energy savings are on the order of 2.8 TBtu and $48.5M over ten years, while also reducing peak load demand. These findings, coupled with the above-presented IEQ benefits, demonstrate the feasibility and attractiveness of engineering solutions that simultaneously improve energy efficiency and IEQ conditions in buildings.

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