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A Computer Simulation Appraisal of Nonresidential Low Energy Cooling Systems in California

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Abstract

An appraisal of the potential performance of different Low Energy Cooling (LEC) systems in nonresidential buildings in California is being conducted using computer simulation. The paper presents results from the first phase of the study, which addressed the systems that can be modeled, with the DOE-2.1E simulation program.

The following LEC technologies were simulated as variants of a conventional variable-air-volume system with vapor compression cooling and mixing ventilation in the occupied spaces:

- Air-side indirect and indirect/direct evaporative pre-cooling
- Cool beams
- Displacement ventilation

Results are presented for four populous climates, represented by Oakland, Sacramento, Pasadena and San Diego. The greatest energy savings are obtained from a combination of displacement ventilation and air-side indirect/direct evaporative pre-cooling. Cool beam systems have the lowest peak demand but do not reduce energy consumption significantly because the reduction in fan energy is offset by a reduction in air-side free cooling. Overall, the results indicate significant opportunities for LEC technologies to reduce energy consumption and demand in nonresidential new construction and retrofit.

Introduction and Scope of the Study

Cooling of Commercial Buildings in California

Space cooling in commercial buildings in California accounts for ~5% of the state's total annual electrical energy consumption, i.e. ~14,000 MWh in 1999 (Brown et al. 2002). The peak demand in 1999 was 7.1 GW, which is ~14% of the total for the state. There is significant potential to reduce this consumption, since the conventional HVAC systems that provide most of this cooling typically do not take full advantage of the climate conditions in California.

Low Energy Cooling Systems

Low energy cooling systems use a variety of approaches, either singly or in combination, to reduce the energy consumption and peak demand associated with the cooling of occupied spaces:

- **Eliminate or reduce chiller use**—Dissipating heat directly to the environment, e.g. evaporative cooling, natural ventilation
- **Cool spaces more effectively**—Allowing higher temperature air or water to be supplied to condition the space, e.g. displacement ventilation, radiant cooling
- **Shift/smooth peak demand with thermal mass**—Increase the effectiveness of pre-cooling and load smoothing using exposed slabs and raised floors
- **Improve distribution system efficiency**—Reduce leakage and thermal losses from duct systems or use water instead of air to reduce parasitic losses

Many of these technologies hold the promise of significantly lower energy consumption and electricity demand. However, they are often quite sensitive to climate conditions. The aim of the study reported here is to assess the energy and peak demand performance in California climates, for those low energy cooling (LEC) systems that can be simulated adequately using the DOE-2.1E simulation program (Winkelmann et al. 1993). These systems are:

- **Indirect/Direct Evaporative Cooling**—Ventilation air is cooled either by direct evaporation into the air stream or by evaporation into an air stream that is coupled to the ventilation air stream via a heat exchanger see **Figure 1**. Five combinations were modeled:
 - Direct only
 - Indirect only (outside air on wet side)
 - Indirect/direct (outside air on wet side)
- **Cooled Beams**—The occupied space is cooled by circulating cool water through exposed fin-tubes in the ceiling—see **Figure 2**. The temperature of the water is significantly higher than in conventional air systems, allowing greater direct use of cooling towers to reduce the use of refrigeration systems. This assumes that any latent load is met by dehumidifying the outside air supplied to meet the minimum ventilation requirement. The output of cool beams is mainly convective and their position in the ceiling results in mixing of the air in the space. Modeling of cool beams is described by Winkelmann et al. (2000)
- **Displacement Ventilation**—Air is supplied at floor level and at low velocity to avoid mixing—see **Figure 3**. The effective comfort temperature is approximately mid way between the supply and extract temperatures, so higher supply air temperatures can achieve the same level of comfort, allowing refrigeration system use to be reduced or eliminated.

Figure 4 shows the baseline system, which is a conventional built-up variable-air-volume system with vapor compression cooling and mixing ventilation in the occupied spaces.

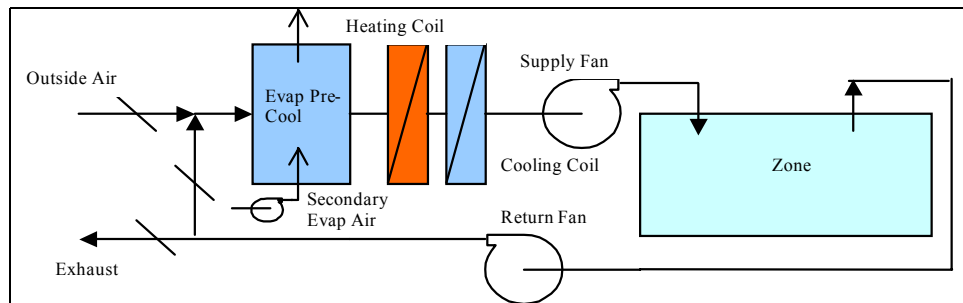


Figure 1. Simplified schematic of evaporative pre-cool on a vapor compression system.

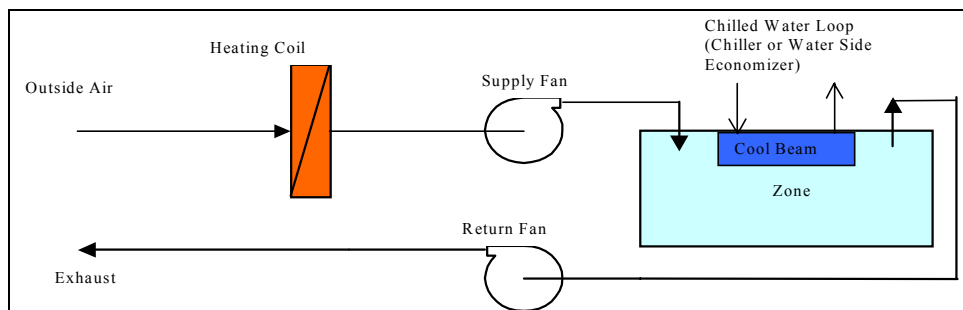


Figure 2. Simplified schematic of a cool beam system.

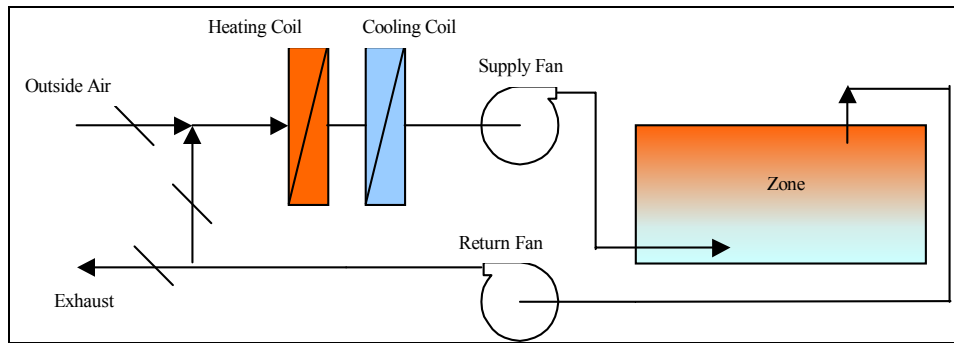


Figure 3. Simplified schematic of displacement ventilation with vapor compression system.

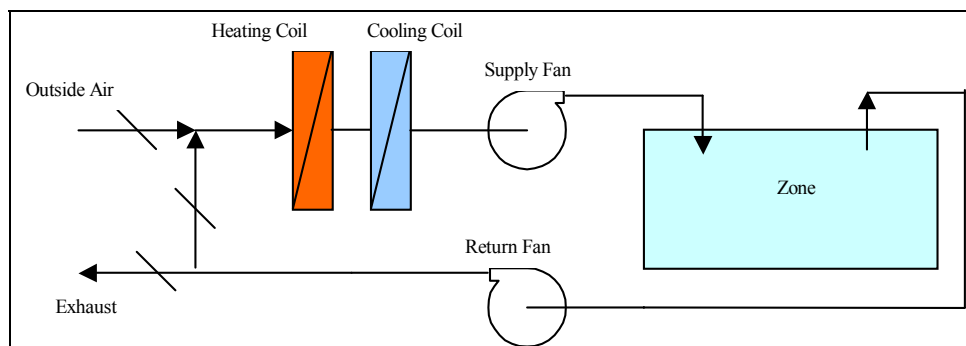


Figure 4. Simplified schematic of the baseline vapor compression built-up system.

Study Methodology

The DOE-2.1E simulation program (Winkelmann et al. 1993) was used to calculate the relative savings potential of the chosen LEC systems. Since DOE-2 was not designed to treat situations in which the zone temperature set-point is not met, modeling was limited to LEC systems that involve additions or modifications to a compressor-based system. Stand-alone systems will be examined using EnergyPlus in a follow-on study.

The purpose of the study reported here was to assess the generic potential of different cooling systems, by predicting their relative performance under a range of conditions chosen as representative of broad classes of buildings. For a particular design brief, the results can be used to generate a short list of cooling system types worthy of further evaluation but should not be used to predict the actual performance that would be obtained from a real building constructed to a specific design and operating under particular conditions.

There are a number of potentially synergistic combinations of the systems listed above. Evaporative cooling complements displacement ventilation because evaporative cooling can more easily achieve the higher supply air temperature required by displacement ventilation. Cool beams are not compatible with displacement ventilation because they produce mixing of the air in the space that disrupts the thermal stratification that is a key attribute of displacement ventilation.

A simplified approach to modeling displacement ventilation was adopted for use with DOE-2.1E. A conventional load calculation is performed and then the supply air temperature is increased from 55°F to 65°F and the zone air temperature set-point is increased from 74°F to 84°F for the Systems and Plant calculations. Since DOE-2 can only model spaces as fully mixed, raising the zone air temperature is the only way to raise the extract temperature. This approach is based on the assumption that, in a displacement system, the dry bulb temperature averaged over the height range of a sedentary person is depressed below the extract temperatures by ~60% of the difference between the supply and extract temperatures (Nielsen 1996).

Rather than simulate a number of different building forms, a generic multistory building model was used. This approach was taken after feedback from practicing design engineers at a meeting held to review this work. Their recommendation was to represent different building configurations by varying the occupancy period and the minimum outside air fraction as shown in **Table 1**, which shows the generic building types that correspond to the combinations of occupancy period and ventilation level that were simulated. The design engineers envisaged that the results could provide them with a quick assessment of the potential applicability of LEC systems during schematic design.

The base model is a modified version of the large office DOE-2.1E prototypical model developed in a previous energy analysis study of HVAC systems (Huang, et al. 1999; Huang, 1999). The building has six stories and a basement, with a total adjusted floor area of 105,000 sf, and the total number of occupants is 354. On the recommendation of the design engineers, the six main floors have a plug load density of 2.5 W/sf. The lighting power density of 1.2 W/sf was selected to satisfy California's Title-24 Building Standard. All four versions of the model shown in **Table 1** have the same internal load densities. The building envelope characteristics were selected to satisfy the requirements of Title-24 in the climate zone being simulated.

Table 1. Occupancy/Ventilation Regimes Covered In The Study

	Economizer: 15% Minimum Outside Air	100% Outside Air, No Economizer
12 Hour Occupancy	Commercial Offices Retail	Laboratory
24 Hour Occupancy	Hotels Supermarkets High Rise Residential	Hospitals

System performance was simulated in each of the 16 California climate zones, although only the results for four climate zones (CZ3=Oakland, CZ7=San Diego, CZ9=Pasadena, CZ12=Sacramento) that are representative of the most populated areas of California are presented in this paper. Results for all 16 climate zones are presented in the final report to the CEC (Bourassa et al. 2002). The original, i.e. pre-1992, California Thermal Zone (CTZ) weather tapes were used in preference to the 1992 revised weather tapes since they contain weather data from actual locations within each climate zone rather than hypothetical average conditions in each CTZ that are not indicative of the weather in any specific location.

System Sizing

The fans, cooling coil, chiller and cooling tower in the baseline system were sized for each climate zone using the autosizing facility in DOE-2. The combined efficiency of the fan, drive and motor was assumed to be 0.68. The maximum turndown for the VAV systems was taken to be 0.33 and the fans were assumed to have variable speed drives.

A key determinant of the benefit of low energy supplemental cooling systems is the trade-off between the reduction in the energy consumption of the conventional system and the parasitic losses associated with the low energy cooling system. Particularly important are the increases in fan energy consumption resulting from the pressure drops across any additional heat exchangers. The baseline system was assumed to have a pressure drop, under design conditions, of 3.5 inches of water on the supply side and 1 inch on the return. The direct evaporative cooling element was assumed to add 0.25 inches and the indirect evaporative cooling element was assumed to add 0.75 inches, both on the primary side and the secondary side. The effectiveness of the direct and the indirect cooling elements was assumed to be 0.85 and 0.65, respectively.

Results

Baseline performance

Figure 5 shows a comparison of the energy use intensity of the baseline building in the Oakland climate zone to the distribution of actual energy use intensities for commercial office buildings in that climate zone, as contained in the California Energy Commission's California End Use Study (CEUS) database. The comparison was performed using

the Cal-Arch on-line benchmarking tool (<http://poet.lbl.gov/cal-arch/>). One reason why the energy use intensity of the baseline is high is that it uses designers' assumptions about plug loads (2.5 W/sf). As long as designers feel the need to make conservative (i.e. high) assumptions about plug loads, these assumptions need to be included when producing design guidance, which is one of the aims of the part of the study reported here. Another part of the study, not reported here, will examine relative system performance using a plug load in the range more representative of real building operation (0.6 to 1.0 W/sf). The model used here has a whole building electrical power density of ~ 5.5 W/sf.

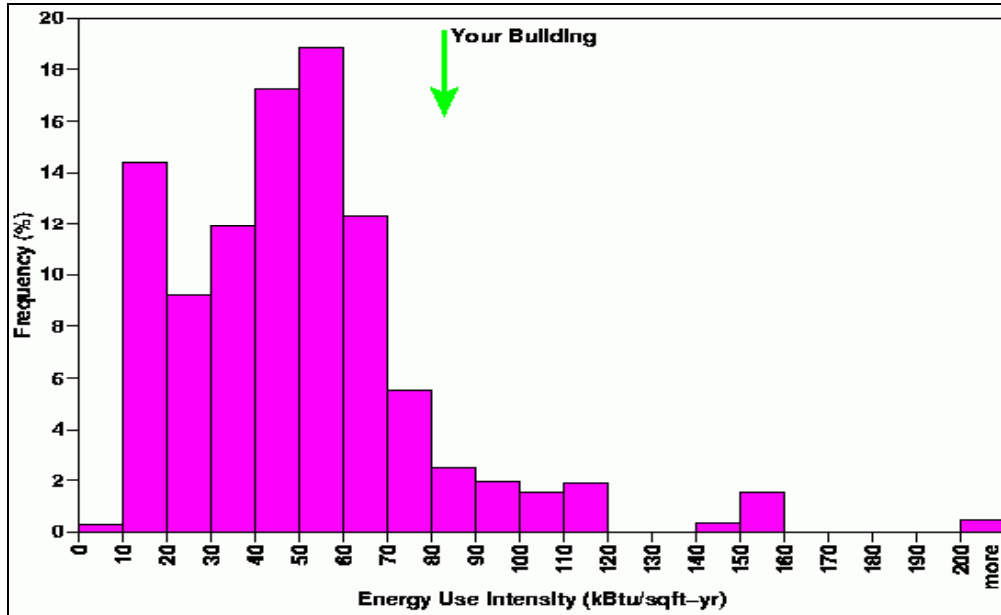


Figure 5. Cal-Arch benchmark of the Oakland prototype.

Energy and peak demand comparisons

Tables 2 and 3 show the energy performance results for the different low energy cooling systems, relative to the unassisted conventional system ("Vapor Compression VAV"). Negative numbers indicate reduced energy consumption. The values for the reference conventional system are Energy Use Intensities (kWh/sf.yr). The results, which are discussed in more detail below, indicate substantial energy savings potential for displacement ventilation, particularly in conjunction with evaporative cooling.

Table 2. HVAC Energy Use Intensity Results For Different Systems In Four Climates

Energy Savings - Title-24 envelope with Low Mass Exposure to conditioned space				
System Configuration	% change versus VAV kWh/sf. yr			
	Oakland	San Diego	Pasadena	Sacramento
Evap. Pre-Cool, indirect on outside air	-8.1%	4.4%	-10.5%	-9.6%
Evap. Pre-Cool, ind/direct on outside air	-22.5%	-11.9%	-23.9%	-23.1%
Displ. Vent., vapor compression	-57.3%	-44.0%	-34.0%	-29.5%
Displ. Vent., w/ CompAC + ind pre-cool	-65.3%	-60.4%	-55.4%	-49.5%
Displ. Vent., w/ CompAC + ind/dir pre-cool	-67.9%	-67.9%	-65.4%	-61.9%
Cool Beam, vapor comp.	11.8%	-5.9%	-10.1%	8.2%
Vapor Compression - VAV	3.56	5.06	5.04	4.47

Table 3. HVAC Power Density Results For Different Systems In Four Climates

Peak Demand - Title-24 envelope with Low Mass Exposure to conditioned space				
System Configuration	Peak Demand (W/sf)			
	Oakland	San Diego	Pasadena	Sacramento
Evap. Pre-Cool, indirect on outside air	1.6	2.4	2.2	2.2
Evap. Pre-Cool, ind/direct on outside air	1.5	2.4	2.2	2.2
Displ. Vent., vapor compression	1.4	1.9	2.1	2.1
Displ. Vent., w/ CompAC + ind pre-cool	0.9	1.5	1.7	1.7
Displ. Vent., w/ CompAC + ind/dir pre-cool	0.6	1.4	1.7	1.7
Cool Beam, vapor comp.	1.2	1.6	1.4	1.6
Vapor Compression - VAV	1.7	2.1	2.1	2.1

Table 4 shows the annual load factor, defined as the ratio of the average electric load to the peak load. The average load is obtained by dividing the electric energy consumption for the year by the number of hours (8,760) in a year. A smaller load factor corresponds to a more unfavorable load shape from the utility perspective. A number of the low energy cooling systems have load factor values that are less than the corresponding values for the conventional system, indicating that the majority of the energy savings are obtained at part load conditions. The one exception is the cool beam system, where the load factor is higher than for the conventional system. The reduction in fan-power associated with using water to distribute cooling to the occupied spaces is greatest at times of peak load because of the cube law dependence of fan power on flow rate in VAV systems with variable speed drives.

Table 4.. HVAC Load Factor Results For Different Systems In Four Climates

Load Factor - Title-24 envelope with Low Mass Exposure to conditioned space				
System Configuration	Annual Load Factor			
	Oakland	San Diego	Pasadena	Sacramento
Evap. Pre-Cool, indirect on outside air	0.22	0.25	0.23	0.21
Evap. Pre-Cool, ind/direct on outside air	0.20	0.21	0.20	0.18
Displ. Vent., vapor compression	0.12	0.16	0.18	0.17
Displ. Vent., w/ CompAC + ind pre-cool	0.16	0.15	0.15	0.15
Displ. Vent., w/ CompAC + ind/dir pre-cool	0.21	0.13	0.12	0.12
Cool Beam, vapor comp.	0.37	0.33	0.37	0.33
Vapor Compression - VAV	0.24	0.28	0.27	0.24

Methods of space conditioning

The way in which the space is conditioned can have a significant effect on performance. **Figure 6** compares the energy performance of three different space-conditioning methods in a building with 12 hr/day occupancy and an economizer, such as an office building. System 1 is a conventional mixing ventilation VAV system, System 2 is a displacement ventilation VAV system and System 3 is a cooled beam system in which the ventilation system supplies only the minimum amount of outside air required by the occupants. In all four climates, the displacement ventilation system consumes significantly less energy than the mixing ventilation system, mainly because the higher supply air temperature allows significantly greater use of free cooling, particularly in the relatively mild Oakland climate. The fan energy is slightly less because of the lower pressure drop associated with the under-floor distribution system. The magnitudes of the savings associated with displacement ventilation should be treated with caution pending the availability of a more detailed model of displacement ventilation that is currently being implemented in the Department of Energy's EnergyPlus program (Crawley et al. 2000).

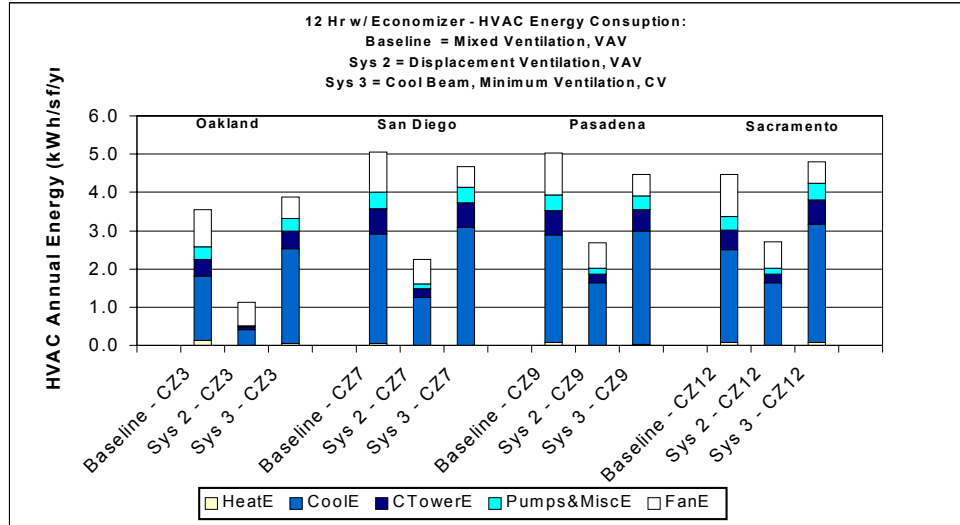


Figure 6. Energy performance of different space conditioning methods for buildings with an economizer and 12 hr/day occupancy.

The cooled beam system has slightly higher energy consumption than the mixing ventilation system in the Northern California climates, where the loss of free cooling associated with a minimum outside air system outweighs the reduction in fan energy. In the Southern California climates, the reduction in fan energy is the dominant effect. Since the temperature of the water supplied to cool beams is typically $\sim 59^{\circ}\text{F}$, one obvious option is to use cooling tower water directly, without the use of a chiller. Preliminary simulation results, not presented here, indicate that the cooling tower needs to be sized for a closer approach to the wet bulb temperature than is conventional practice for chilled water plants if significant benefits from water-side free cooling are to be obtained.

Figure 7 is the corresponding plot to **Figure 6** for a full outside air system, such as would be used in a laboratory building. In this case, the advantage of the displacement ventilation system is even more pronounced since the ventilation load is greater. The calculation of the energy consumption of the cooled beam system assumes that the ventilation rate is the minimum outside airflow rate, i.e. that the requirement is for no recirculation rather than for a high outside airflow rate. The energy consumption is then less than that of the mixed ventilation system in all

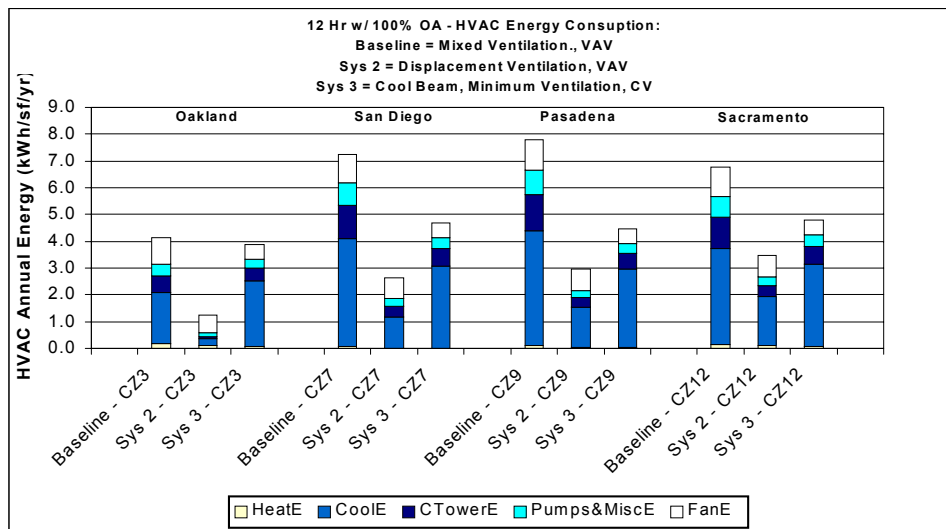


Figure 7. Energy performance of different space conditioning methods for 100% outside air systems and 12 hr/day occupancy.

climates. If a high ventilation rate is required, the performance will be similar to that of the mixed ventilation system and the ventilation air, rather than the cooled beam, will meet the majority of the cooling load. The conclusion is that cooled beams are beneficial if the climate is such that there are only modest savings to be gained from free cooling and/or the use of a water-based system allows the reduction of the ventilation rate and hence the ventilation load.

Evaporative Pre-cooling

Figure 8 shows the benefits of evaporative pre-cooling for mixed ventilation HVAC systems. System 1 is a conventional mixing ventilation VAV system, System 2 has an indirect evaporative cooling stage before the cooling coil and System 3 has an indirect evaporative cooling stage followed by a direct cooling stage before the cooling coil. The evaporative pre-cooling provides only modest improvements. In San Diego (CZ 7), the indirect stage provides negligible benefit. In the other climates, the benefit is partially offset by the significant increase in fan power resulting from the 0.75 in H₂O pressure drop at design flow caused by the heat exchanger for the indirect stage. The addition of a direct stage produces significant additional savings but results in increased humidity in the space that is problematical in San Diego (116 hrs/yr above 70% RH) and has a minor impact in other climates.

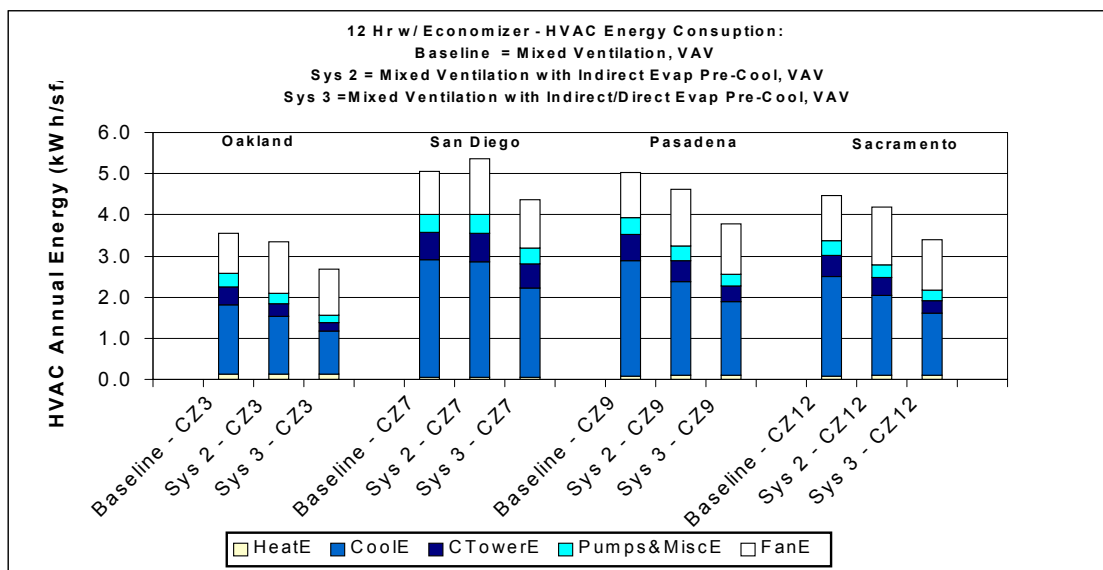


Figure 8. Evaporative pre-cooling for mixing ventilation.

Figure 9 is the corresponding plot to **Figure 8** for displacement ventilation rather than mixing ventilation. In Oakland (CZ 3), the benefit of evaporative cooling is relatively small because the chiller use in the unassisted displacement ventilation system is quite small, so that the chiller savings do not significantly exceed the increase in fan energy. In the other climates, the chiller use, and hence the potential savings, are much greater. The approximate method of modeling displacement ventilation used here does not facilitate the estimation of the humidity in the space; however, the use of direct evaporative cooling with relatively high supply air temperatures can be expected to produce high relative humidities in the lower regions of the occupied space and is not recommended without more detailed psychrometric calculations. In spite of this restriction, the combination of evaporative cooling and displacement ventilation produces very significant reductions in energy consumption, and also in peak demand. The indirect systems were modeled in two configurations, either using outside air or return air on the wet side of the media. In each case studied, the use of outside air resulted in better performance.

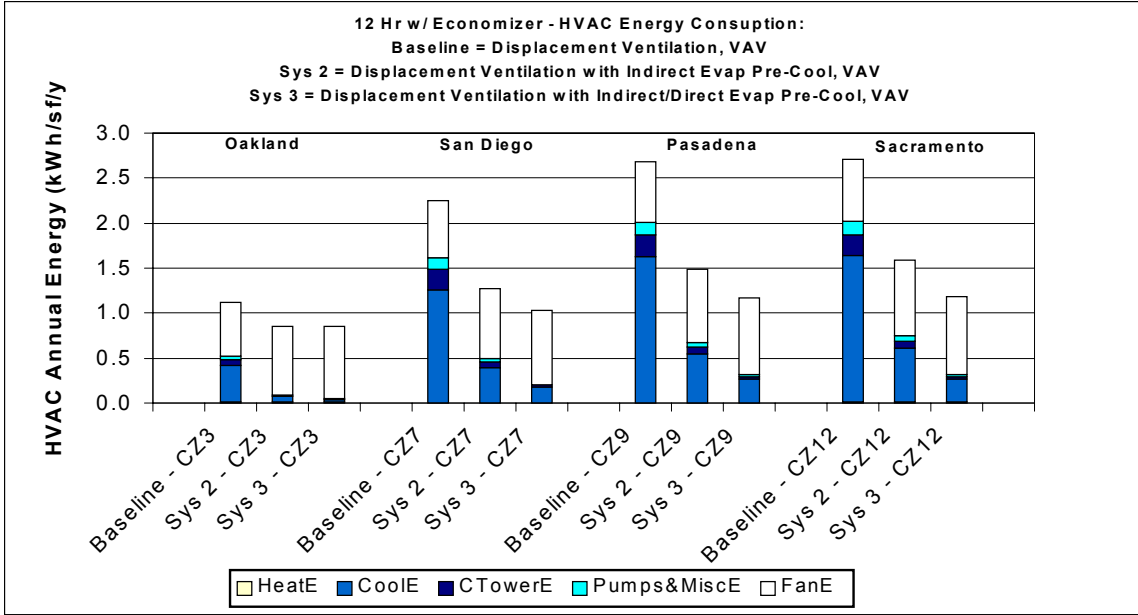
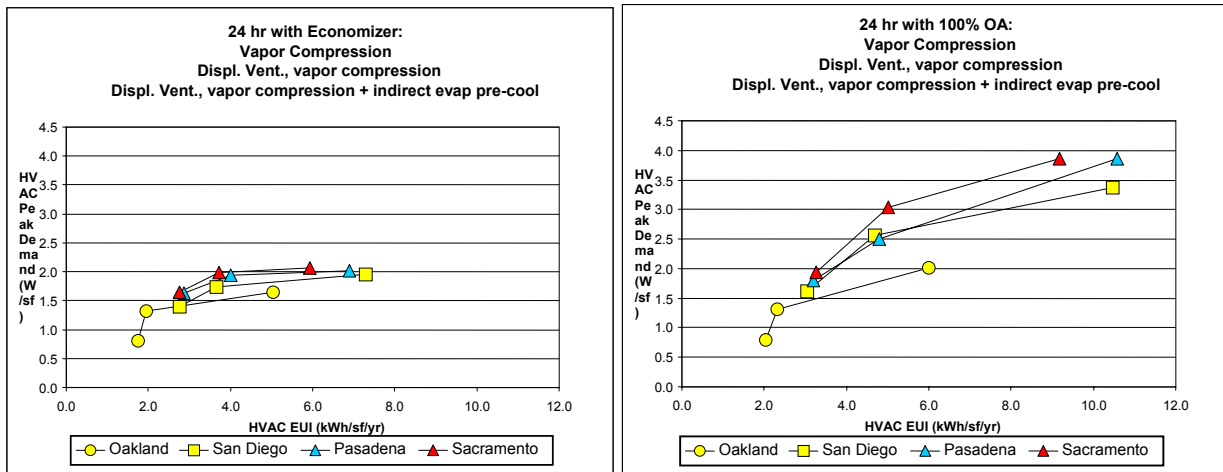


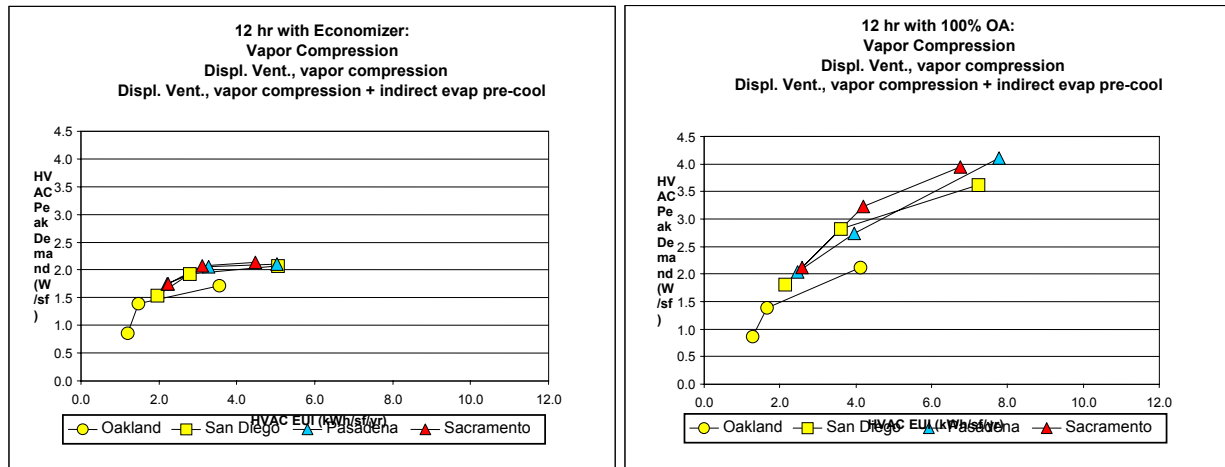
Figure 9. Evaporative pre-cooling for displacement ventilation.

Figure 10 shows the progressive reduction in energy use intensity (EUI) and peak demand of changing from conventional mixing ventilation (upper right of each graph) to displacement ventilation and then adding indirect evaporative pre-cooling. Buildings that need 100% outside air and/or operate 24 hours/day have the largest savings potential in absolute terms. In each case, the fractional reduction in EUI is greater than the fractional reduction in peak demand, although laboratories and other buildings that need 100% outside air and operate ~12 hours/day show only a slight degradation in load factor. The negligible reduction in peak demand on changing from mixing ventilation to displacement ventilation in buildings, such as offices and retail stores, that have economizers is because the ambient dry bulb temperature is greater than the return temperature from displacement ventilation (~85°F) so there is no free cooling. The exception is Oakland, where the ambient dry bulb is 84°F at the time of the peak load.



**Figure 10 continued*

*Figure 10 continued



The addition of indirect evaporative pre-cooling improves the load factor because there is significant potential for evaporative cooling at the time of the peak demand, which tends to occur when the ambient dry bulb temperature is high but the ambient wet bulb temperature is not especially high. The potential for useful evaporative pre-cooling tends to be lower at times when the load is lower because of the availability of conventional free cooling. For displacement ventilation, at least, this somewhat contradicts the conventional wisdom that evaporative cooling has a deleterious effect on load factor.

Conclusions

The way in which spaces are cooled has a significant effect on energy performance. In particular, displacement ventilation systems are able to make significantly greater use of free cooling and evaporative cooling because of their higher supply air temperature. This is apparent in all climates and is particularly so in less severe climates. The quantitative estimates of savings should be treated with caution pending the availability of a validated model of the operation of spaces with displacement ventilation in a whole building simulation program

Evaporative pre-cooling is beneficial in all California climates. The benefits are greater in the less humid regions but are still significant on the coast. Evaporative cooling complements displacement ventilation in all climates, although the benefits in the cooler Northern coastal climates are mainly in peak load reduction.

Fan energy consumption is a key component of system performance. The benefits of evaporative cooling systems are reduced by the additional fan power needed to overcome the increased air-side pressure, in the case of air-side evaporative cooling, or to operate the cooling tower in the case of the water-side economizer.

Peak demand can be reduced by improving distribution system efficiency. Cool beam systems perform better than conventional systems at times of peak load because of the reduced fan-power associated with using water to distribute cooling to the occupied spaces.

Peak demand could be reduced by making use of thermal storage. In particular, low energy cooling systems that store daytime heat gains in the fabric of the building and then dissipate heat directly to the environment at night have the potential to reduce peak demand substantially. These systems will be studied in a follow-on project using the models currently being developed for EnergyPlus.

Acknowledgement

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