Are there Savings in Demand-Controlled Ventilation?

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ABSTRACT

Rooftop units condition a large amount of commercial space. In particular, buildings with high-density but variable occupancy could potentially benefit from demand-controlled ventilation. A variety of factors can impact the efficiency of rooftop units, including: their designed cooling efficiency measured in EER; the presence and operation of economizer cycles that take in more outdoor air when its heat content is lower than air returning to the unit; and the method used to control air quantity—either variable-speed drives or inlet vane dampers. Additional factors that can impact efficiency are: optimizing ventilation sequences, often referred to as demand control ventilation (DCV); adjusting supply air temperature to match needs; and adjusting space set points and unit operation during unoccupied periods.

Demand control ventilation was installed in large theatre complexes through two programs evaluated under the CPUC guidelines. Since DCV are required under 2005 Title 24, these programs focused on older theaters. As part of the effort, evaporator and condenser coils were cleaned, economizers repaired, and a CO2-based DCV strategy installed.

This study instrumented and collected pre and post data for eight rooftop units with constant volume fans to assess an RTU maintenance and DCV effort. This paper discusses methodologies for measuring airflow, air conditioning heat load, and fan operation, and limitations to measuring changes in operation. The study assesses the success of the efficiency measures and reviews operations of three units instrumented by evaluators, identifying operating flaws and other strategies for saving energy in RTUs.

Principal findings from analyzing three DCV sites provide several lessons from the field. (1) Each unit metered reveals a unique story contributing to preliminary observations of estimated electric energy savings ranging from 6% to 24%. Anticipated savings vary strongly with the climate. Harsher climate sites (zone 15) need to be monitored to get a full perspective on the savings from this program. (2) An empirical estimate of demand savings for these units requires that the post-retrofit period be warm enough to trigger the second-stage cooling. Ideally, M&V for this type of application should be staged so the post-retrofit period starts no later than the beginning of August. (3) Selection of data logger and sensors, placement of OSA sensors, and logging intervals impact data collection and analysis.

Program Description

The objective of energy-efficiency programs sponsored by two California utilities is to reduce the air conditioning load in low-use or no-use screening rooms in movie theater complexes. The program proposed to accomplish this by cleaning the condenser and evaporator coils of the AC units and installing DCV controls with CO2 sensors to tailor the amount of fresh (and hot) outside air released into screening rooms to the number of occupants in the rooms.

Part of the theory of DCV application is to conserve energy by admitting lower quantities of outside air when it is unnecessary. Typically, a unit may have set its minimum outside air too high to serve the occupancy of partially occupied periods. With an active CO2 sensor controlling the outside air damper, the minimum outside air can be lower and the minimum outside air will be increased only when justified by readings from the CO2 sensor. The role of the economizer is to allow an abrupt increase in outside air quantity only when it is necessary, allowing much lower outside air to be admitted at other times.

AC units run more efficiently when the coils are clean. DCV controls use the amount of CO2 present in the return air as a proxy for the number of occupants in a room and adjust the flow of fresh, outside air (that needs cooling) into the room to provide an adequate amount of code-specified ventilation per occupant. In theory, the units will also demand less energy on hot summer days, reducing their contribution to the California system peak.

The program fielded with the two utility sponsors late October 2007. The original program plan was limited to theaters in climate zones 6, 8, 9, and 10, but targeted theaters in climate zones 8, 9, and 10 where cooling energy consumption is higher. During the first quarter of 2008, because of the late start and low program participation, the program expanded to include customers in climate zones 13, 14, 15, and 16. It also changed to allow heat pump retrofits.

Site Selection

Metering protocol for CPUC-evaluated programs required both pre- and post-retrofit monitoring of the air conditioning units during the time California's system peak would typically occur (i.e., August and September). Our evaluation team worked closely with the third-party implementer to identify theater complexes with multiple air conditioning units that would be undergoing coil cleaning and the DCV retrofit during the cooling season. The metered sample was a convenience sample. A random sample could not be drawn since not all participants had been identified at the time metering approached the cooling season, and some installations were already complete. The evaluation plans called for metering one theater complex from each of the three targeted climate zones (i.e., zones 8, 9, and 10). Responding to program changes, we attempted to select one of the three monitored sites from coastal climate zone 6, one from the more moderate inland climate zones 8, 9, or 10, and one from the more extreme inland climate zones 13, 14, 15, or 16.

Sites were metered in zones 8 and 9. However, no sites were available or qualified for pre-post monitoring in zone 6 or the inland zones during the metering time frame. We conducted pre-post metering at four sites at Rancho Santa Margarita, which is southeast of Los Angeles, about 25 miles from the coast, and four sites in West Covina, 10 miles east of the center of Los Angeles. Units ranged in capacity from 8.5 to 15 tons.

Metering Methodology

Data loggers were installed at eight packaged air conditioning units at two different multiplex theater complexes. Four air conditioning units were monitored per site. Table 1 indicates the data collected, quantity, and meter device and model. The collected data were intended to provide the information required to independently estimate the ex-post savings resulting from coil cleaning and the installation of DCV controls. Field activities were designed to:

1) Verify baseline conditions and assumptions;
2) Verify measure installations;
3) Verify energy savings assumptions; and
4) Correlate installation reports with participant interviews.

Table 1. Logged Measurements at Each Unit

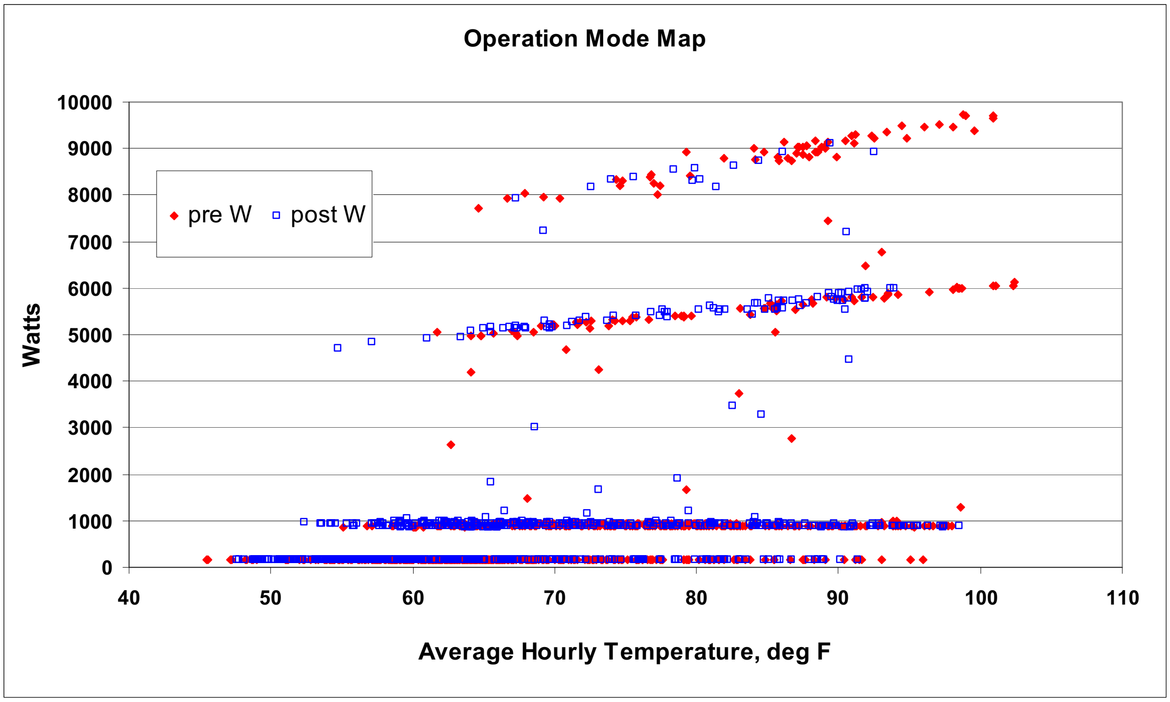
Monitoring Equipment Summary			
Quantity	**Model**	**Device**	**Point**
1	S-THB-M008	Temp/RH sensor	unit return air (air leaving the space and returning to the unit; CO2 sensor placed in this airstream to capture CO2 effects of heightened occupancy)
1	S-THB-M008	Temp/RH sensor	unit supply air (air leaving RTU and entering the ductwork, reflecting actions of coil and heater)
3	S-THB-M008	Temp/RH sensor	unit mixed air (reflects mixed temperature between return air and outside air admitted at the dampers)
1	S-UCC-M006	Pulse input adapter w/ WattNode, Continental Control Systems	total unit kWh
1	S-UCC-M006	Pulse input adapter w/ WattNode, Continental Control Systems	supply fan kWh
1	T-SET-265-005	Pressure differential transducer	unit air pressure differential (0-5"WC)
1	U30-VIA	CO2 sensor (by others)	CO2 control input signal (0-5 vDC)
3	T-MAG-SCT-020	20 amp CT	supply fan power (460v / 3 phase)
3	T-MAG-SCT-050	50 amp CT	total unit power (460v / 3 phase)
2	T-WNB-3D-480	Watt Node, Continental Control Systems	kWh transducer (supply fan & total unit)
1	H21-002	HOBO micro station	outdoor air temp/RH (outside air, OSA)
24 voltage probe sets for WattNode devices (3 phase) - 2 sets / RTU			
18 AWG shielded 3-conductor cable for pressure differential transducer - 1 / RTU			

Analytic Methodology

Once the metered data were collected and downloaded, we aggregated the information and worked it into several perspectives to understand and finally quantify the effects of the monitored DCV applications. Primary data were taken in 5-minute or 15-minute intervals. In its raw form, the data were quite variable, and trial plots showed the data in clouds with no clear form. This was to be expected with short-interval data, and the first step in the analysis was to devise aggregations to reveal the underlying events. The first level of aggregation was hourly averages and/or sums. In addition to the hourly averages, we identified the hourly maximum power. This hourly information was then worked into the review plots shown in Figure 2 and Figure 3 to examine the system operating modes and the amount of outside air being drawn in by the monitored unit.

Figure 2 shows the average hourly outside air temperature versus the maximum power for that hour. This review format quite clearly reveals the operating modes for this monitored unit. It shows there is a 1,000 Watt constant speed fan, and it shows the operation of two compressor stages operating in the ranges of 5,000–6,000 W and 8,000–10,000 W. Note in these compressor stages, the compressor power increases with increasing temperature. In this figure, the points are color-coded: red for pre-retrofit and blue for post-retrofit.

Figure 2. Operational Mode Map



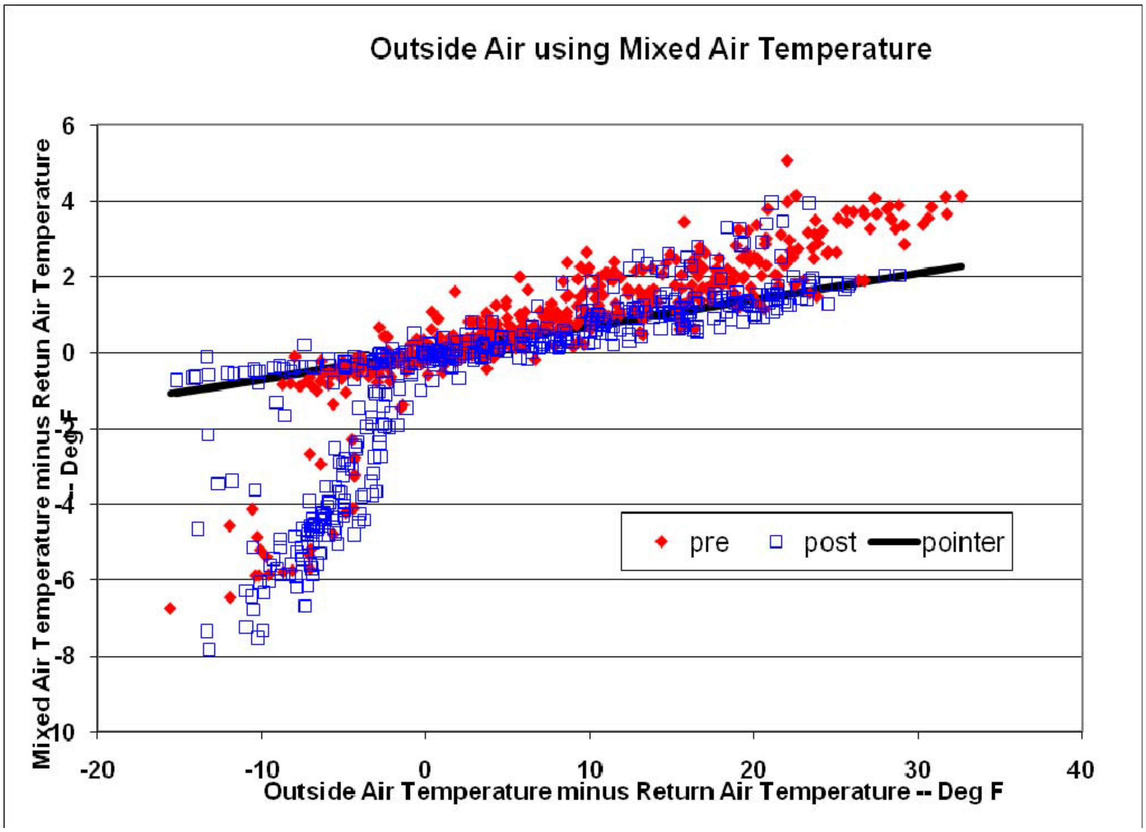
In this case, there is no significant difference in compressor or fan power pre- and post-retrofit. However, had there been a fan speed adjustment or a significant refrigeration system change, the pre- and post-retrofit points would have shown a clear displacement relative to one another. It is with reference to this plot that we look for evidence of a retrofit-induced change in demand at the maximum observed temperature, (in this case, about 100 deg F). This maximum observed temperature is meant to be a proxy for the outside air temperature at utility peak.

In Figure 3, the hourly temperature information is plotted in a common format used to assess the level of outside air induced into the unit. The horizontal axis is the temperature difference: average hourly minus the return air temperature. This temperature difference is essentially the difference between the outside air and conditioned space. The vertical axis is the temperature difference between the mixed air and the return air. At a maximum, this temperature difference will be the same as the difference between the outside air and the return air because there is no mix; only outside air is being admitted. At a minimum, the absolute value of the temperature difference between the mixed air and the return air will be zero, because the mixed air is composed entirely of the return air and no outside air is being admitted. The choice of using these temperature differences as axes was informed by a common air mass mix equation so that the geometric slope revealed in this plot is the same as the percentage of outside air admitted to the circulation air stream.

For example, in a plot such as this, the slope of the pattern of points indicates the fraction of outside air mixed into the unit. In this figure, the red pre-retrofit points cluster about a black line labeled as pointer. The slope of the line in this example is about .13, indicating an air mix with 13% outside air. It is evident in Figure 3 that most of the post-retrofit activity had an even lower air mix of about 6%.

Note the steeply sloped cluster of red and blue points in the lower left of the plot. Likewise, these points in the lower left show a slope of .75, evidence that an operating economizer admits about 75% outside air. Note that this plot includes all operating intervals and the majority of data are post retrofit because equipment operated longer in that state. Each point represents the conditions prevailing for one hour (the 15 minute data logger interval points were aggregated to an hourly average).

Figure 3. Outside Air Plot



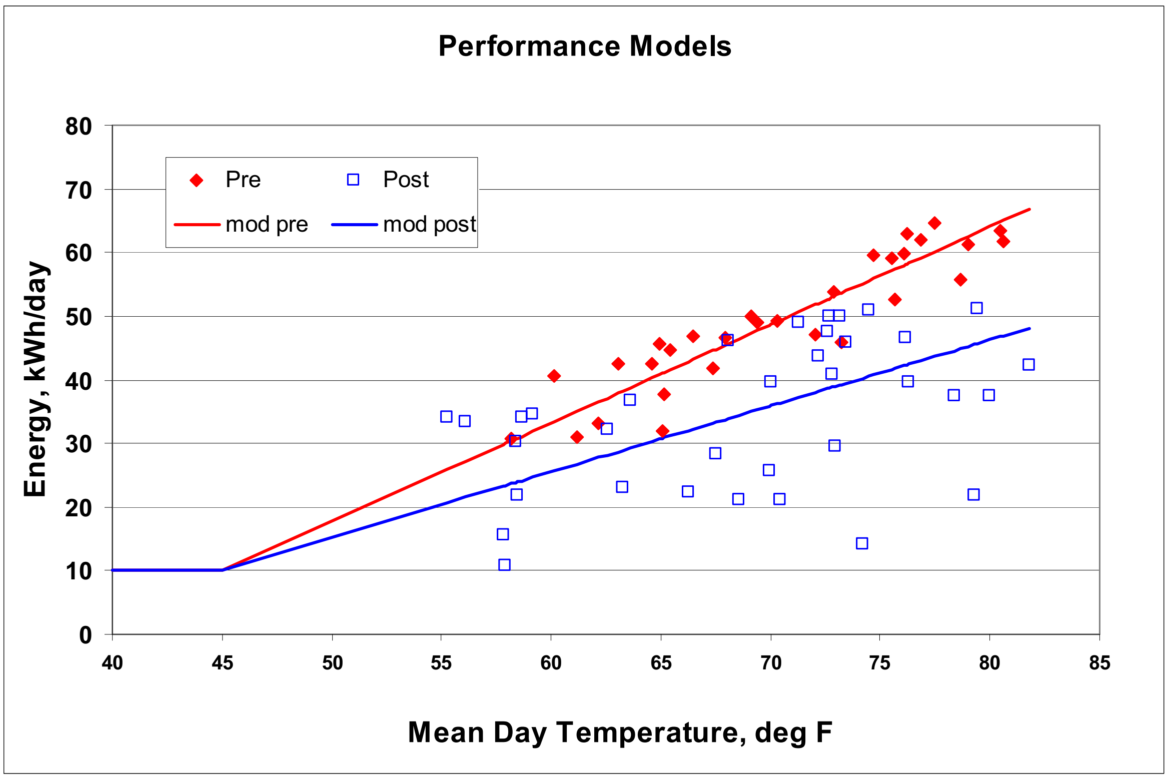
Pre-period extends 9/17/08 to 10/20/08; Post-period extends 10/20/08-11/25/08. Average hourly values

With reference to the plot in Figure 3, we assess the effect of the retrofit on the amount of outside air induced into the unit. In this case, there is clear evidence there is less outside air admitted during the post-retrofit operation, and the economizer system is working. Both these conditions are approximately as intended in the retrofit.

While the empirical observations in Figure 2 and Figure 3 may show clear evidence of the change caused by the retrofit, they do not lead directly to an estimate of the annual energy impacts of the change. The estimate of the annual energy impacts requires an additional level of aggregation, from hourly to daily. Building monitoring in general has shown daily aggregations of energy and temperature "behave well" because they have the same period as the principal drivers of building energy use (i.e., weather and occupancy). Thermal transients that typically have periods of the order of one to several hours, will significantly obscure the more detailed data with much shorter periods (one minute and five minutes, etc.).

For each monitored day, there will be a point characterized by the average outdoor temperature for the 24-hour period (td) and the total electric energy used by the unit (kWh/dayd). These daily aggregates are plotted as in Figure 4, kWh/day versus average daily temperature. This figure shows a situation where the pre-retrofit points show an approximate linear relationship to the average daily temperature, with the post-retrofit points showing less energy use that the pre, but also showing no clear pattern. The interpretation of this information and the derivation of performance models from it relies on use of other results and techniques pertaining to M&V applied to rooftop units.[1] These points include all occupancy periods, including days where nothing is happening. The pre-period shows a static situation where nothing changed from day-to-day, and the damper position is not moved in response to occupancy variations. The post-period, damper activity is controlled by the CO2 sensor, responding to variations in occupancy, and accordingly shows a wider scatter. The low points are non-use days. It appears the CO2 sensor is operating as intended.

Figure 4. Performance Plot



Pre-period extends 9/17/08 to 10/20/08; Post-period extends 10/20/08-11/25/08. Average daily values

M&V applied to rooftop units in general has been complicated by the fact that rooftop units respond to internal loads (heating and cooling) of the particular space served by the rooftop unit. The energy use of an individual unit will not be very visible in whole building energy use, especially if there are several units, and, for cost reasons, the M&V cannot be extended into the building in an attempt to determine the applicable loads.

This other research[2] has shown an individual rooftop unit has a clear operating signature that can be defined without reference to the conditions of the associated space. In fact, the conditions of the associated space caused the operation of the unit, but a simple signature in terms of average daily

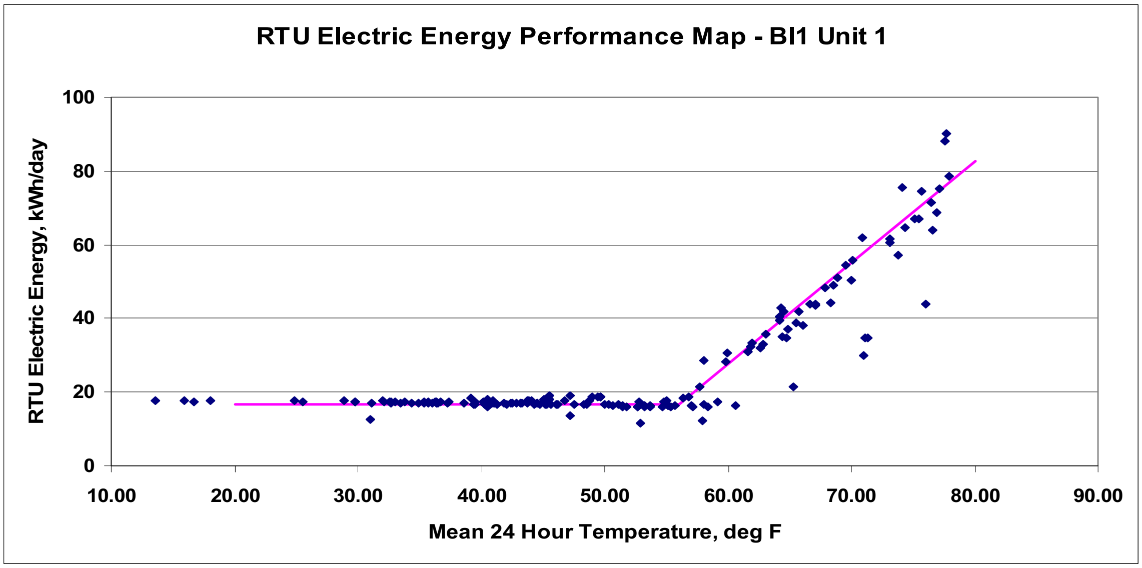
[1] Commercial Rooftop HVAC Energy Savings Research Program—Final Project Report. Prepared by NBI for the Northwest Power and Conservation Council. 2009. Available on the NBI website: www.newbuildings.org

[2] Ibid.

temperature and energy, kWh/day, can characterize the full operation of the unit without explicit knowledge of those conditions.

In the ideal, the signature for a rooftop unit will be as in Figure 5, which was drawn from about one year of observations on a very regularly operating unit.

Figure 5. Electric Energy Signature



Period extends from Sept 2007 to Aug 2008. Average daily values

Figure 5 shows the idealized energy performance signature of a rooftop unit to be composed of a horizontal line representing fan power alone and a sloping line representing compressor operation, which increases approximately linearly with temperature. These data cover almost a one year period on a very regularly operated building. The low points below the sloping line represent the first cooling week of the year, while the building was already cooled from winter conditions immediately preceding this week. The temperature at which the horizontal and sloping lines meet is the balance point temperature. Often, summer monitoring data will not be of sufficient span to include the horizontal portion of the signature, but that portion can usually be deduced by inspection of the detailed data for the fan operating patterns. Based on this work, the empirical model of rooftop unit energy use will be taken as a simple, broken line model, consisting of a horizontal portion and a sloping portion with an intersection at a balance point temperature. The horizontal portion refers to the baseload, and is essentially daily total fan energy, independent of compressor operation. The sloping portion is added to the horizontal portion, and is driven by the energy used in the compressor subsystem. The slope is a rather complex result of the specific factors in the conditioned space. These factors include internal gain to the space, external temperature of the space, the amount of fresh air admitted to the space, the cooling setpoint temperature, and the efficiency of the cooling unit itself. The fact that these conditions resolve into an apparent linear relationship, we believe is a fortunate coincidence.

It should be noted that the relatively clean performance signature of Figure 5 comes from a regularly operating building, while the buildings being studied here, multiplex movie theaters, are conspicuously not regular in operation, with strong activity on weekends and minimal activity otherwise. In fact, DCV is most effective in situations where there are long, often irregular, unoccupied periods when ventilation can be significantly restricted. Therefore, in this particular project, the typical data (as in Figure 3) will be more scattered than data shown in Figure 4. Note in Figure 3, the lines identified as the pre- and post-performance models are constrained to pass through the data in such a way that the total energy predicted by the models will be equal to the total energy indicated in the data. This modeling approach is intended to produce performance models representing the mean performance of the unit rather than the performance associated with a particular high or low day. This is different than the typical fitting criteria used in most regression work. The data for this site as well as most of the others in this particular research work involves a high variation in occupancy, especially between week-ends and week-days. The fitted line is intended to construct the long term average weekly energy use, which combines high and low use days. We found that our initial attempts to use a squared regression criteria were seriously biased with respect to reconstructing the original energy use records.

The final step to an annual energy use estimate is to use the performance model with a histogram of the average daily temperatures for a normal year at the monitored site (or a prospective site). The process is illustrated in Table 2.

Table 2. Calculation of Annual Energy Use

			Modeled energy use (kWh/day)		Annual energy use (amount per day times number days in bin) (kWh/yr)		
bin days	**Temp bin (deg F)**	**bin avg temp (deg F)**	**pre**	**post**	**pre**	**post**	**savings (kWh/yr)**
2	35-40	37.5	17	17	34	34	0
5	40-45	42.5	17	17	85	85	0
7	45-50	47.5	17	17	119	119	0
49	50-55	52.5	17	17	833	833	0
74	55-60	57.5	24.8	21.4	1,837	1,583	254
113	60-65	62.5	40.5	30.2	4,574	3,409	1165
95	65-70	67.5	56.1	39	5,332	3,700	632
19	70-75	72.5	71.8	47.7	1,364	907	457
1	75-80	77.5	87.4	56.5	87	57	30
0	80-85	82.5	103.1	65.3	0	0	0
0	85-90	87.5	118.7	74.1	0	0	0
0	90-95	92.5	134.4	82.9	0	0	0
0	95-100	97.5	150	91.6	0	0	0
				Total	***14264***	***10726***	***3,538***

In the example shown in Table 2, the unit shows clear annual electric energy savings, with most of the savings occurring in the 60–65 and 65–70 deg F temperature bins. The use of TMY to temperature histograms to express regional weather may need to be corrected for microclimatic factors such as conditions on a roof surrounding the RTU.

Typical DCV Operation Illustration Applied to Movie Theatres

At all of the monitored units, a pronounced weekly pattern is evident in CO2, Figure 6, and energy use, Figure 7. These figures both show higher levels of activity repeating approximately every 6 to 7 days. In addition, the energy usage map in Figure 7 shows the fan operates every day from about noon until midnight, and energy use greater than fan energy, about 1 kW, is due to compressor use for cooling the space in the early afternoon and on some evenings when attendance is high. This CO2 data shows that the high metabolic activity in these buildings is in the early evenings (people go to movies at night). This also corresponds to the metabolic heat gain to the space and the cooling load. This is cooling situation occurs in the early evening, as opposed to most cooling situations in the office and retail sectors that occur in the early afternoon. The fortunate aspect of this situation is that the outside air has cooled enough in the evening so that it can be used for economizing.

Figure 6. CO2 Map

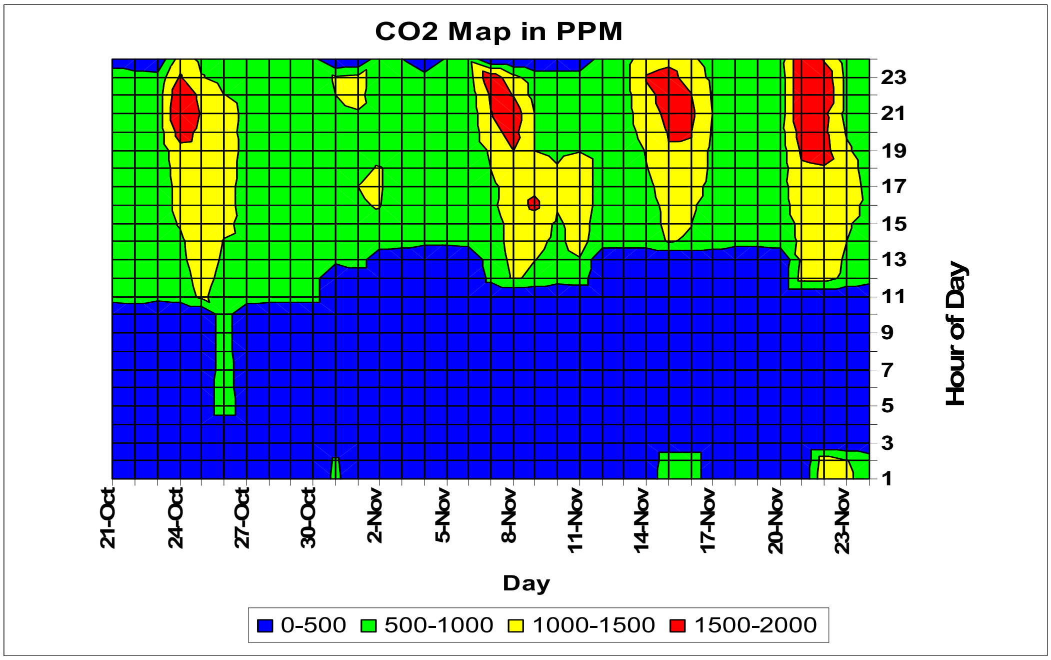
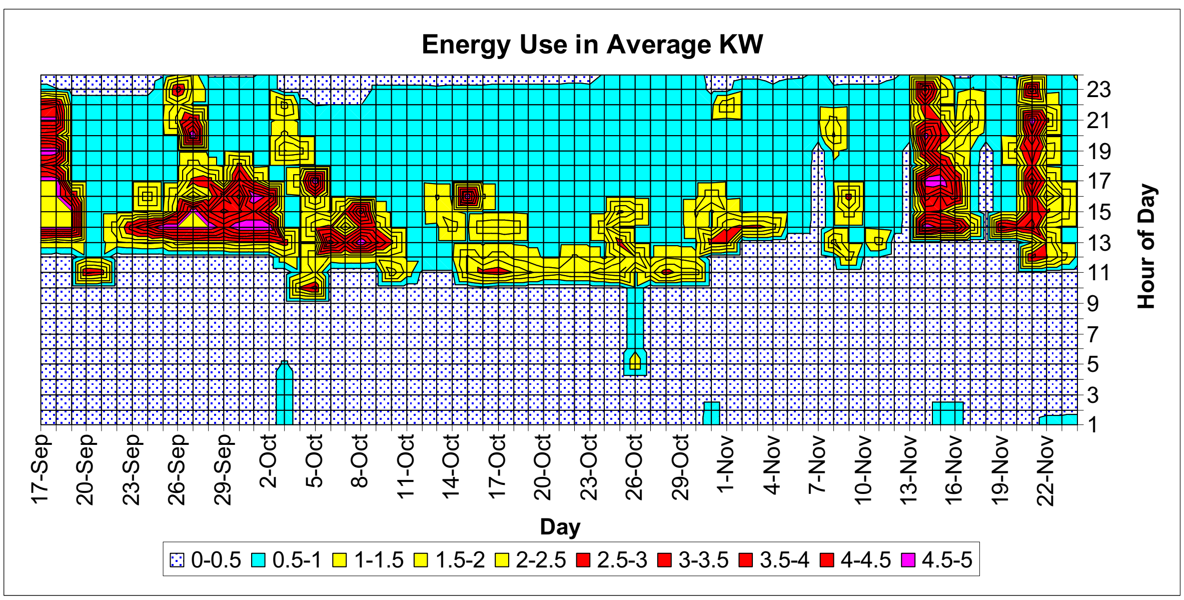


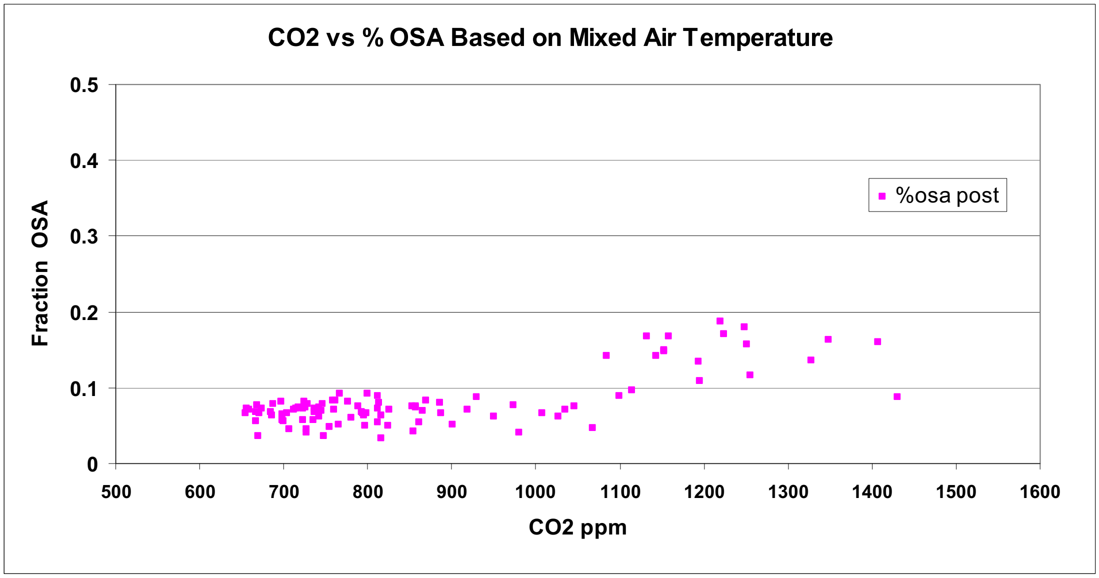
Figure 7. Energy Map



Note the compressor operation on approximately September 26th, associated with warm weather (about 100 deg F peak day temperature). By contrast, the compressor operation evident on days such as November 6 and 22, with peak day temperatures of 75–80 deg F, is associated with high internal gains.

The theory of operation of the DCV is to close the dampers at all times, except when the level of CO2 rises. The operation of this logic is evident in Figure 8, which shows the percent OSA versus the CO2 level. It is evident that when the CO2 levels rise above 1100 ppm, the dampers are opened slightly to supply extra ventilation.

Figure 8. CO2 versus. OSA



Post-period extends 10/20/08-11/25/08. Average hourly values

Findings

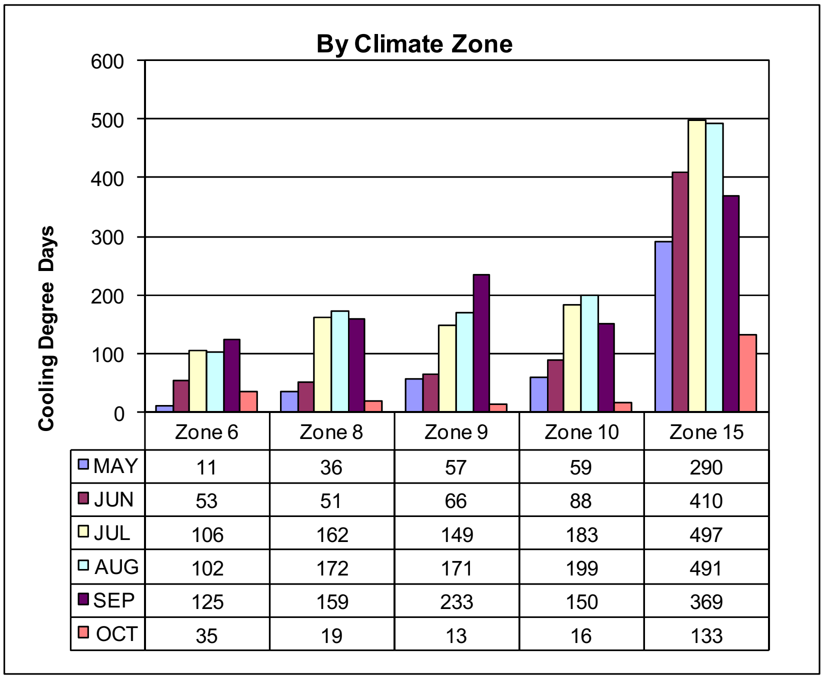
The findings for the three units analyzed in detail for this paper are summarized in Table 3. These units clearly showed evidence of electric and gas energy savings due to the applied DCV measures. An empirical estimate of demand savings for these units requires that the post-retrofit period be warm enough to trigger the second-stage cooling. At these sites, the post-retrofit period began in late September, leaving only a few hours of second-stage operation in the post-retrofit period. Therefore, the demand savings estimates are based on only a few hours of anecdotal evidence. Ideally, M&V for this type of application should be staged so the post-retrofit period starts no later than the beginning of September.

Table 3. Summary of Results for Three Monitored DCV sites

Site	Observed OSA change	Observed Demand Change	Annual Electric Energy Savings	Annual Gas Energy Savings	Estimated Electric Savings	Estimated Gas Savings
	Climate zone 8/9 – Metered Sites				Climate zone 13 - Inland site	
		Watts	kWh/yr	therms/yr	kWh/yr	therms/yr
WC 295	Yes	500 W	3,538	46	8,123	53
WC 286	Yes	No	300	4	520	10
RSM 292	Yes	300 W	2,500	7	3,800	35

It should be noted all these sites are in a very moderate climate, with most of the average daily temperatures in the range of 50–75 deg F, California climate zone 8 and 9. It is well known that DCV savings depend strongly on the outside air temperature regime from which they are derived. Therefore, we exercised the energy usage models derived for these sites for the harsher climate that would be found in the populated desert regions of Southern California, climate zone 13. Table 3 also includes estimates of the energy savings from these retrofits had these sites experienced the harsher climate 40–50 miles inland. Table 3 shows that in a harsher climate, estimated savings from these retrofits would be substantially larger. Figure 9 illustrates the difference in Cooling Degree Days (CDD) between climate zones, showing zone 15 clearly has greater potential to capture savings in this type of application.

Figure 9. Cooling Degree Days by Climate Zone



	Zone 6	Zone 8	Zone 9	Zone 10	Zone 15
MAY	11	36	57	59	290
JUN	53	51	66	88	410
JUL	106	162	149	183	497
AUG	102	172	171	199	491
SEP	125	159	233	150	369
OCT	35	19	13	16	133

Each Unit has a Unique Story

The highest savings were at unit WC-295, with about 24% electric energy savings. This unit had an unusually high minimum outside air of about 50% in the pre-retrofit period. The retrofit reduced the minimum outside air to 20% during high CO2 events and to about 5% otherwise. This high reduction in ventilation caused the high electric energy savings. There were also demand savings of about 500 W. These demand savings are attributable to reducing the mixed air temperature at peak periods by reducing the outside air mix from about 50% to less than 20%. In part, these high savings are due to an initial situation of the unit that admitted too much outside air. This could have been prevented by adequate commissioning, but it is difficult to tell in the absence of careful measurement, i.e., visual inspection only, how much outside air is being admitted by what appear to be almost closed dampers.

The next highest savings were at unit RSM-292, with about 20% electric energy savings. These electric energy savings are attributable to reduced ventilation. There are also demand savings of about 300 W. The air temperatures measured at this unit were not consistent enough to achieve precise measurements of the outside air mix.

The lowest savings were observed at WC-286, with about 6% electric energy savings. This unit showed very clear evidence of reduced outside air due to the retrofit, but the unit already had a low minimum outside air setting of 12% in the pre-retrofit period. The retrofit succeeded in lowering the mean post-retrofit outside air to about 7%, but, during high CO2 episodes, the outside air was in the range of 12–15%. There were no demand savings at this unit because, during peak periods and high CO2, the unit would have about the same outside air mix as the pre-retrofit period.

Lessons Learned From the Field

1) Anticipated savings vary strongly with the climate. Harsher climate sites need to be monitored to get a full perspective on the savings from this program. The original plan called for monitoring in climate zone 15, but no sites were available. Because modeled savings appear high (Table 3), metering in climate zone 15 is still warranted.

2) The post-retrofit period should not begin any later than early August if accurate estimates in changes in demand are required. Good energy estimates can be made with post-installation in August, but demand estimates require the highest level of compressor operation.

3) Percent OSA requires the OSA sensor be placed beside the unit on the shady side. The intake location is subject to night exfiltration that would bias the temperature readings. Therefore, the sensor should be outside the intake. The OSA sensor should also be ventilated (i.e. have a small fan at the intake of the unit, not a centralized sensor that applies to all units). The centralized sensor was intended to take measurements applicable to all rooftop units at the site, but this placement did not work well. There seems to be microclimate differences from unit to unit; we did not expect these differences to be large enough to disrupt the measurements, but they appeared to be. Also, should there be a failure of the weather station, the experiment will be lost at all the associated sites.

4) To log outdoor air and RH requires two more sensors attached to the J30 data logger on the unit. The J30 logger on the unit has no room for more sensors, and some room must be made. Therefore, the RH from mixed air sensors should be removed, and only dry bulb temperatures be taken. This means the sensors for mixed air will be cheaper, smaller, and easier to place in the unit. If RH of the mixed air is needed, it can be calculated in the post-data processing from the RH in the outside air and return air streams. The elimination of mixed air RH would free up three channels on the J30, which could and should be used for OSA. Ideally, four dry bulb air temperatures should be used for the mixed air instead of three.

5) Fifteen-minute level data can be used, but it is too coarse; rather, five-minute or one-minute data should be used.