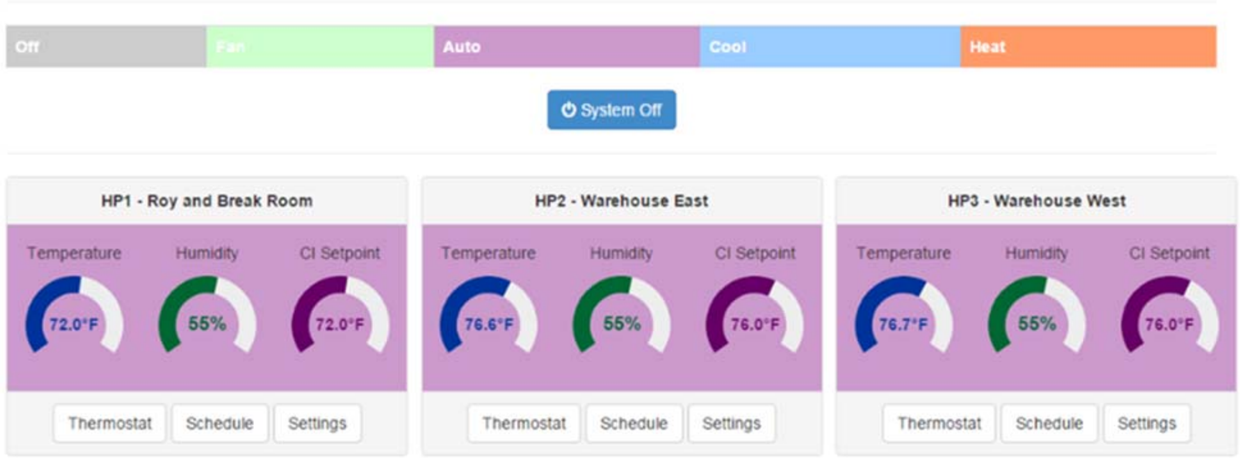
# HVAC MANAGEMENT SYSTEMS WITH DYNAMIC ENERGY AND DEMAND OPTIMIZATION

San Diego Gas & Electric
Emerging Technologies Program
Technology Assessment Report
Project ID ET14SDG7011



**Prepared for:**
Kate Zeng and Matt Smith
San Diego Gas and Electric Company
[www.sdge.com](http://www.sdge.com)

**Prepared by:**
Antonio Corradini, PE and Akane Karasawa, PE
Alternative Energy Systems Consulting, Inc.
[www.aesc-inc.com](http://www.aesc-inc.com)

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For more information, contact ETinfo@sdge.com.

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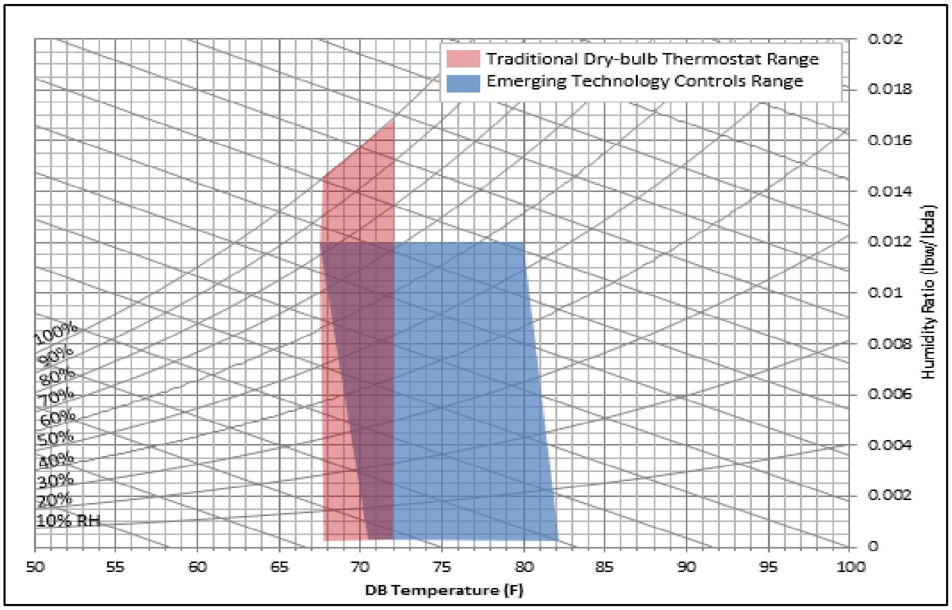
# EXECUTIVE SUMMARY

The emerging technology (ET) presented in this report is an HVAC management system with dynamic energy and demand optimization designed for commercial rooftop units (RTUs) and split system applications. The ET replaces a traditional thermostat with multiple sensors that measure dry-bulb temperature and relative humidity in a zone. The information from the sensors is sent to an on-site controller, which relays the information to a cloud server for storage, analysis, and reporting. The on-site system then dynamically evaluates zone conditions using the sensor data, weather data (as a proxy for radiant heat), schedule information, as well as specific zone-by-zone properties such as air flow rates that are stored in the system's database. The controller then activates fans, compressors, and furnaces as applicable to maintain a "comfort" setpoint. The control mechanism differs from traditional thermostats, where fans and compressors are activated based solely on a specific dry-bulb temperature versus the whole comfort temperature relative humidity range.

The collected data were also used to compare the thermal zone conditions before and after the installation of ET using the ASHRAE 55 thermal comfort zone as a guideline. The results revealed that the ET was able to improve the zone condition within the thermal comfort zone limits, therefore improving the occupants comfort.



In this report, the energy savings associated with the proposed ET were evaluated by using the field test results obtained from two test sites. The technology yielded savings due to several factors:

- Reducing the run time of RTUs with scheduling and soft start strategies.
- Reducing the run time of the compressor by applying a "comfort" setpoint and therefore increasing the fan-only operating range.
- Analytical fault detection and diagnostics (FDD) to alert building operators of non-catastrophic conditions that might waste energy.

The data analysis of the first field test showed a 29% reduction in energy used across five heat pumps and the second field test showed an overall 38% reduction in energy used across nine AC units due mainly from advanced scheduling. The calculations also found that the ET achieved 8% savings during occupied times at the second site, which could potential qualify for utility incentive.

Finally, the ET was tested for its demand response and permanent demand reduction capabilities. The results showed that the ET was able to reduce the combined peak power of a facility by 30% by coordinating the operations of multiple units during a DR event.

# ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AESC | Alternative Energy Systems Consulting |
| ASHRAE | American Society of Heating, Refrigerating, and Air Conditioning Engineers |
| CPUC | California Public Utilities Commission |
| DEER | Database for Energy Efficient Resources |
| DX | Direct Expansion |
| EE | Energy efficiency |
| EER | Energy efficiency ratio |
| EISG | Energy Innovation Small Grant |
| ET | Emerging technologies |
| FDD | Fault detection and diagnostics |
| M&V | Measurement and verification |
| OAT | Outside air temperature |
| RTU | Rooftop unit |
| SDG&E | San Diego Gas and Electric |

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# INTRODUCTION

Packaged air conditioning units, often referred to rooftop units (RTUs), account for 46% of cooling equipment installed in commercial buildings, according to the Department of Energy Buildings Energy Data Book (Department of Energy, 2012a). Approximately 27% of all electric energy consumed in commercial buildings is attributed to RTU operations. However, RTUs generally receive minimal maintenance and run until a major failure, at which point they must be serviced or replaced. The average efficiency of RTUs in service in 2010 was 11.2 EER when the efficiency of best-available RTU on the market was 13.9 EER (Department of Energy, 2012b).

There are many retrofit options to improve the RTU operation efficiency available on the market. However, the ET presented in this report introduces a unique control algorithm for RTUs. The new control system allows for maximizing zone thermal comfort while reducing peak power and energy consumption. Understanding thermal comfort as a mean to reduce HVAC energy consumption has recently attracted much attention. For example, NREL is conducting a research in their newly constructed “Comfort Suite” to understand the effect of temperature, humidity, and air flow on human comfort (Hicks, 2015). Besides energy savings, the technology is capable of demand response and will also help increase the life expectancy of RTUs by reducing compressor cycling.

The primary goal of this study is to confirm the energy savings, peak demand reduction, and demand response capabilities of the advanced controller for RTUs. SDG&E sponsored AESC to conduct field measurements and verification to evaluate the energy and demand saving potentials of the proposed technology. The functionality and the plausibility of the technology was also reviewed and confirmed. Finally, the advanced controller’s energy saving features were evaluated for possible incorporation into existing incentive programs. The research and development of the evaluated technology was partially funded by the California Energy Commission’s Energy Innovation Small Grant Program (EISG).

# BACKGROUND AND TECHNOLOGY

The emerging technology (ET) targets the historically underserved market of small commercial spaces with single zone packaged units. A packaged air conditioning unit typically consists of compressor(s), fan(s), furnace(s), and a thermostat. RTUs are controlled by thermostats located in the interior zones and can operate in various configurations, such as always on, scheduled by time, or on as needed based on the temperature set-point (auto). Programmable thermostats can setback temperature setpoints and can be scheduled to turn the units off when the space is unoccupied. On the other hand, many old pneumatic thermostats operate the units without any setback for evening or weekends and can easily be left on all the time.

Improperly set or programmed thermostats can cause occupant discomfort and energy waste. However, thermostats are often left unchecked for their calibration and settings unless the unit fails and creates a maintenance action item. Therefore, HVAC inefficiency stemming from the thermostat settings or defects can go unnoticed for a long time. The proposed technology remedies the issue by replacing thermostats with high-accuracy sensors and controls that can be monitored real time at a remote location through a cloud based interface.

## MARKET OVERVIEW OPPORTUNITY

The ET targets packaged RTUs that are predominantly used in stand-alone retail, small office buildings, and medium office buildings (W. Wang, 2012). The California Commercial End-Use Survey shows that offices and retail buildings in the SDG&E region consumes 3,570 GWh or 42% of total electricity consumed by all commercial buildings and that 28% of the energy consumed is used for cooling and ventilation (Itron, Inc., 2006).

## APPLICABLE CODES AND STANDARDS

The current 2013 non-residential Title 24 requires shut-off and reset controls for all space-conditioning systems. Additionally, all thermostats are required to have setback programming capabilities with a minimum of four separate setpoints per 24-hour period. For unitary single zone air conditioners, heat pumps, and furnaces, Occupant Controlled Smart Thermostats (OCSTs) are also required. These thermostats are capable of responding to demand response signals in the event of grid congestion and shortages during high electrical demand periods. The emerging technology presented in this report meets all of the above code requirements.

## EMERGING TECHNOLOGY DESCRIPTION

The ET is designed to retrofit packaged RTUs and consists of sensors, an on-site controller, and an optional cloud-based server. The ET sensors are mounted to replace the existing system thermostats. Once installed, the system controls RTU fan(s), compressor(s), and furnace(s) and provides analytical FDD to alert building operators of non-catastrophic conditions requiring attention. The sensors communicate with a building-wide controller, which is continuously connected to the cloud. The control strategy was developed to improve occupant comfort, increases compressor life through reduced cycling, and reduces energy consumption and peak demand.

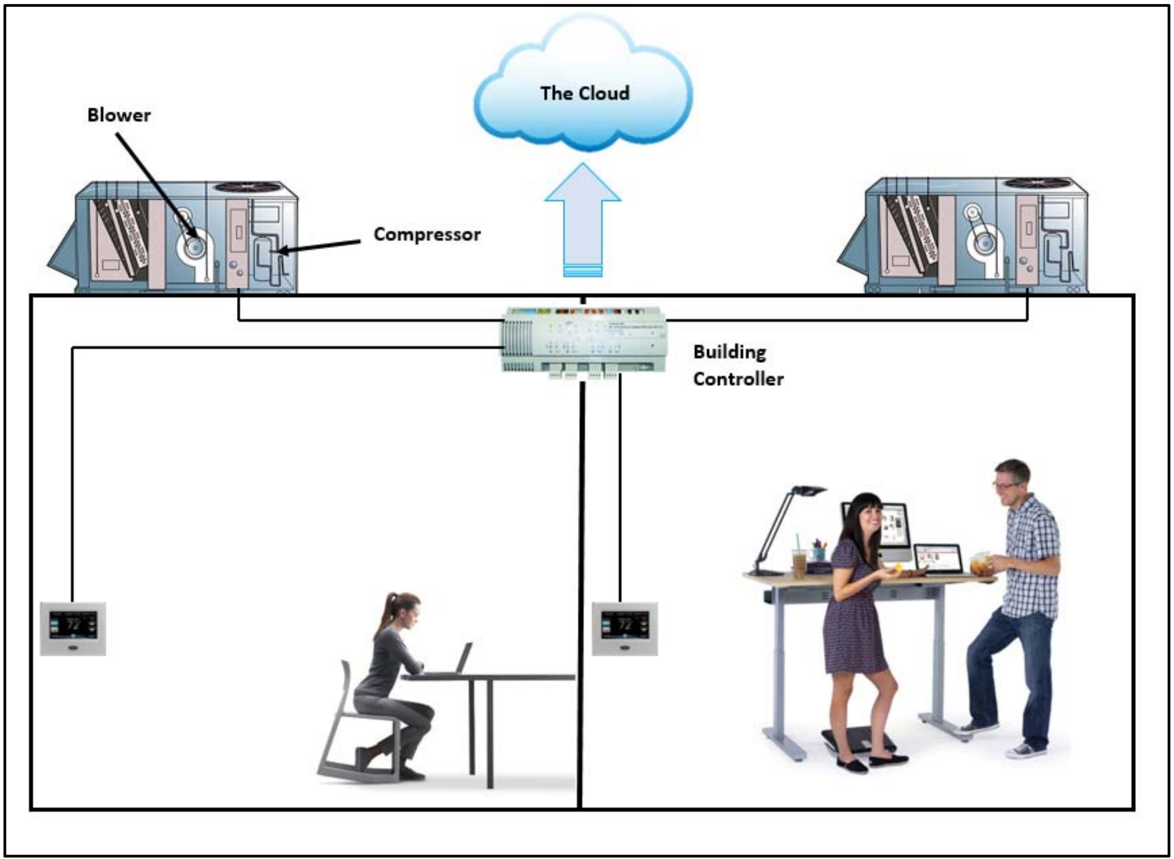

FIGURE 1: REPRESENTATION OF PROPOSED ET

1. Thermal Comfort

The ET measures dry-bulb temperature, relative humidity, OAT as proxy for radiant heat, and has user settings for occupant activity intensity level to determine fan, compressor, and furnace operations. The space conditions are controlled to be kept within thermal comfort zone limits rather than a set dry-bulb temperature.

Thermal comfort zone is defined as the zone environment where 80% of sedentary or slightly active persons find thermally acceptable. Shaded regions in Figure 2 below represent the summer and winter thermal comfort zones as defined by ASHRAE Standard 55. To prevent warm discomfort in the summer, relative humidity below 60% is also recommended (ASHRAE, 2013).

The ET takes advantage of the fact that the thermal comfort zone extends to regions with dry-bulb temperature up to 80°F at low humidity conditions. With its innovative control strategy, the system allows zone dry-bulb temperatures to float up while still maintaining comfort, which results in reduced compressor operating hours and energy savings.

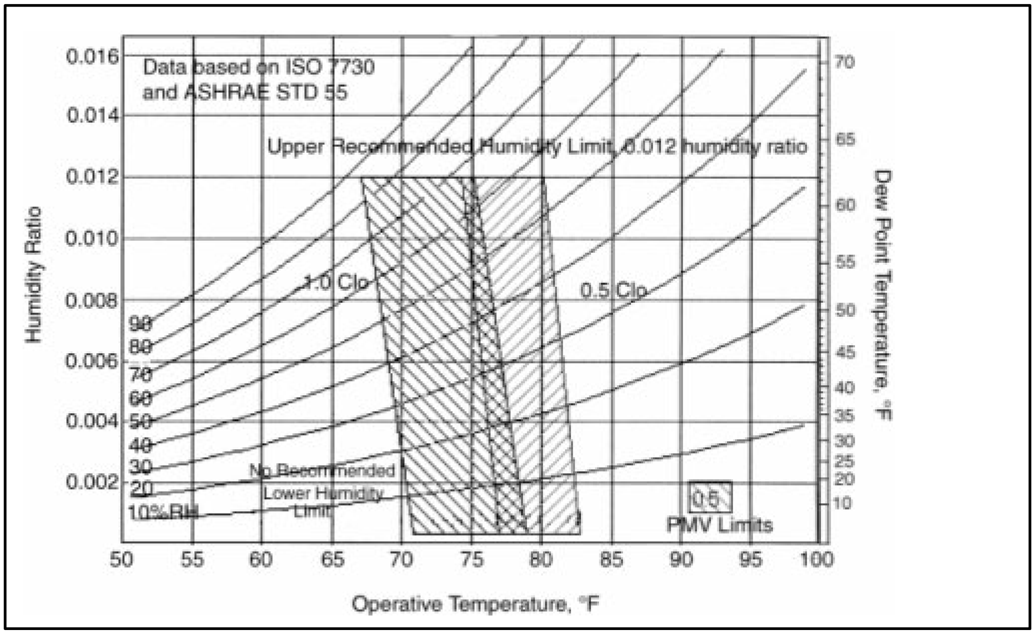

FIGURE 2: ASHRAE STANDARD 55 THERMAL COMFORT ZONES

### 2. Compressor Cycling

The median lifetime of commercial RTUs is 15 years (Department of Energy, 2012c), which is short compared to other mechanical equipment. One of the reasons for this low life expectancy is the short cycling that many single zone RTUs are subjected to. The proposed technology will reduce short cycling which may extend the life of the most critical piece of the unit, the compressor.

### 3. Energy Consumption

As described above, the ET evaluates zone comfort in terms of dry-bulb temperature, relative humidity, and OAT as proxy for radiant heat. It activates the fan and compressor accordingly to maintain a “comfort” setpoint rather than a specific temperature. As the result, the compressor run time and energy consumption are often reduced compared to traditional systems. The energy savings are also achieved from scheduling, where units are programmed to operate only during occupied hours, therefore reducing compressor and fan run hours.

### 4. Peak Demand

The proposed technology’s controlling algorithm allows the user to specify a kW-cap across all controlled RTUs, which can reduce peak demand. The demand limiting algorithm can maintain the total demand below the kW-cap by cycling compressors within the facility. The cycling strategy is dynamic to zone conditions, such that when the building load cannot be met with the kW-cap, all zones deviate from their setpoints at approximately the same rate. The demand limiting feature can be exploited continuously or during DR events.

# PROJECT OBJECTIVE

The primary goal of this study is to confirm the energy savings and demand reduction of the advanced controller for RTUs. The energy savings will be assessed based on field measurements. The functionality and the plausibility of the technology will also be reviewed and confirmed. The following list summarizes the objectives of this project:

1. Describe system setup, operations, and functionality,
2. Quantify energy and peak demand savings,
3. Analyze factors that may cause variations in energy savings under different circumstances such as different base RTUs or climate zones,
4. Review utility programs with respect to their present applicability to this technology and provide recommendations on how utilities could further support this technology,
5. Research the potential market size and possible barriers to adoption,
6. Gather and present customer feedback,
7. Suggest possible improvements to the technology,
8. Assess risks introduced by this technology.

# MEASUREMENT AND VERIFICATION PLAN

The M&V plan for the emerging technology assessment was performed through field measurements of installed technology. Plans were developed for two sites to collect data that captures the energy consumptions of RTUs during typical building operations before and after the technology implementation. The instrumentation and M&V approach was agreed upon by all involved parties: AESC, SDG&E, and the vendor supplying the emerging technology product.

## HOST SITES OVERVIEW

M&V was performed at two sites. The first test site is operated by an electronics manufacturer and is a single story commercial building located in Poway, California in Climate Zone 10. The building consists of office spaces along the perimeter and manufacturing and warehouse spaces in the core. General building features are listed in Table 1.

TABLE 1: BUILDING ONE FEATURES

| Building Feature | Building Attribute |
|---|---|
| **Year built** | 1998 |
| **Size** | Approx. 12,000 $ft^2$ |
| **Location** | Poway, CA |
| **California Climate Zone** | 10 |
| **Occupancy type** | Office/Laboratory |
| **Occupancy schedule** | Monday – Friday, 08:00-17:00 |
| **Building Management System** | None |
| **Mechanical System Summary** | Constant Volume, Packaged, Single Zone Heat Pumps |

The building has nine single zone heat pumps, but only six were included in this study:

- Heat pump units serving zone 1 and 7 were excluded because the vendor had used the zones as test labs and therefore the retrofit had already been implemented prior to this study.
- Zone 4 was also excluded because it is a storage room, where the air conditioning system is not used.

All of the heat pumps are packaged RTUs with cooling capacities between three and five tons. All RTUs have constant-volume fans and single-stage constant-speed compressors with rated cooling efficiency of 9.5 EER. The RTUs do not have economizers and therefore they constantly supply minimum outside air. All units are over 15 years old as they were installed when the building was built.

Each heat pump is connected to its own thermostat, which is configured to heat only mode, cool only mode, or both, depending on the zone served. Two heat pumps (HP-2 and HP-3) commonly serve a manufacturing space and the rest each serves an office space. Prior to retrofit, the RTUs operated on weekly time schedules. Refer to Table 2 for the baseline thermostat schedules and settings.

### TABLE 2: BUILDING ONE EXISTING THERMOSTATS SCHEDULE

| | Zone 2 | | Zone 3 | | Zone 5 | | Zone 6 | | Zone 7 | | Zone 8 | | Zone 9 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** | **M-F Prgrm** | **SS Prgrm** |
| **Time ON** | 7:30 AM | 5:00 AM | 8:00 AM | 5:00 AM | 8:00 AM | 7:00 AM | 8:00 AM | 7:00 AM | 8:00 AM | 7:00 AM | 7:30 AM | 7:00 AM | 7:30 AM | 7:00 AM |
| **Heat Temp** | 68 | 45 | 68 | 45 | 68 | 45 | 68 | 45 | 68 | 45 | 68 | 60 | 68 | 45 |
| **Cool Temp** | 75 | 88 | 75 | 88 | 74 | 88 | 74 | 88 | 74 | 88 | 71 | 80 | 73 | 88 |
| **Time ON** | 5:00 PM | 6:00 PM | 5:00 PM | 6:00 PM | 5:00 PM | 6:00 PM | 5:00 PM | 6:00 PM | 1:00 PM | 6:00 PM | 5:00 PM | 6:00 PM | 5:00 PM | 5:00 PM |
| **Heat Temp** | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 68 | 45 | 45 | 60 | 45 | 45 |
| **Cool Temp** | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 88 | 73 | 88 | 88 | 80 | 88 | 88 |
| **Time ON** | | | | | | | | | 5:00 PM | | | | | |
| **Heat Temp** | | | | | | | | | 45 | | | | | |
| **Cool Temp** | | | | | | | | | 88 | | | | | |
| **system setting** | Heat | | Auto | | Cool | | Auto | | Auto | | Auto | | Cool | |
| **fan setting** | Auto | | Auto | | Auto | | Auto | | Fan On | | Auto | | Auto | |

The second test site is a single-story office building owned by the County of San Diego. The building is located in San Diego, California in Climate Zone 10. The building consists of a lobby, a conference room, office spaces, and common areas. General building features are listed in Table 3 below.

### TABLE 3: BUILDING TWO FEATURES

| Building Feature | Building Attribute |
|---|---|
| **Year built** | 1960s |
| **Size** | *26,000 ft²* |
| **Location** | San Diego, CA 92120 |
| **California Climate Zone** | 10 |
| **Occupancy type** | Office |
| **Occupancy schedule** | Monday – Friday, 08:00-17:00 |
| **Building Management System** | None |
| **Mechanical System Summary** | Constant Volume, Packaged, Single Zone Direct Expansion (DX)/furnace units |

The building has four split systems and ten packaged DX units on the rooftop. M&V was performed on ten DX units that served offices and common areas. The split systems were excluded from this study because they serve closed areas with atypical loads such as server rooms and a storage room.

All RTUs have constant-volume fans and constant-speed compressors and ran 24/7 prior to retrofit. The RTUs do not have economizers and therefore they supply minimum constant volume of outside air. All units are between 10 and 15 years old. Each unit is connected to its own thermostat, which is not programmed. Refer to Table 4 for zone characteristics and thermostat schedule and cooling setpoints.

### TABLE 4: COUNTY OF SAN DIEGO EXISTING THERMOSTAT SCHEDULES

| Unit ID | AC1 | AC2 | AC3 | AC4 | AC5 | AC6 | AC7 | AC8 | AC9 | AC10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Rooms | 101-106 | TBS/Lunch room | 116, 120, 121 | Communication Room | 201-212 | 214-220 | Reception/Lobby | 222,223, 248-256 | Conference room | 221 |
| T-stat SP °F | 72 | 74 | 69 | 70 | 76 | 72 | 73 | 74 | 78 | 73 |
| Occupied Hours | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM | M-F: 6AM - 7PM |

FIGURE 3: AERIAL VIEW OF THE COUNTY OF SAN DIEGO BUILDING

## DATA COLLECTION

At the first test site, six T/RH Hobo loggers were placed at the thermostats throughout the building and one T/RH Hobo logger was placed on the roof to sample ambient temperature and relative humidity data every one minute. The baseline measurements were performed from December 12, 2013 to March 2, 2014 and post-retrofit measurements from March 6, 2014 to June 1, 2014. Current transducers and voltage probes were also placed on units HP-1 through HP-9 on the roof to collect power data at one-minute interval.

The following table summarizes the location and type of data collected at the first site:

TABLE 5: SITE 1 DATA COLLECTION SUMMARY

| Location | Quantity | Equipment | Data collected | Frequency |
|---|---|---|---|---|
| Outdoor | 1 | Hobo T/RH logger | Ambient temperature (dry-bulb)<br>Ambient relative humidity | Every one minute |
| Thermostats | 9 | Hobo T/RH logger | Zone temperature (dry-bulb)<br>Zone relative humidity | Every one minute |
| Heat pumps (rooftop) | 9 | eGauge logger | Power (kW) | Every one minute |

FIGURE 4: T/RH HOBO LOGGER PLACED AT THE THERMOSTAT DURING BASELINE MEASUREMENTS

At the second test site, baseline measurement was performed for two months from September 2014. The data were collected from 14 T/RH Hobo loggers placed at the thermostats throughout the building as well as one T/RH logger placed on the roof. These loggers were set to sample T/RH every 1 minute. Current transducers and voltage probes were also placed on units AC1 through AC10 on the roof and set to sample current at one-minute interval.

Post-installation measurement started briefly after the installation in November of 2014. The data was continuously collected until September of 2015. For this site, the post-implementation power data was collected with eGauges.

The following table summarizes the location and type of data collected at the second site:

TABLE 6: SITE 2 DATA COLLECTION SUMMARY

| **Location** | **Quantity** | **Equipment** | **Data collected** | **Frequency** |
|---|---|---|---|---|
| Outdoor | 1 | Hobo T/RH logger | Ambient temperature (dry-bulb)<br>Ambient relative humidity | Every one minute |
| Thermostats | 14 | Hobo T/RH logger | Zone temperature (dry-bulb)<br>Zone relative humidity | Every one minute |
| AC units (rooftop) | 10 | eGauge logger | Power (kW) | Every one minute |

Although outside air temperature and relative humidity were collected at the site, NOAA weather data was used in the analysis to minimize inaccuracies in the measurements.

# DATA ANALYSIS

The energy savings, peak demand, and demand response evaluations in this report were done by comparing the energy consumptions of RTUs before and after the ET implementation. All data were collected in one-minute intervals. However, the analysis was performed by also combining data into hourly averages to reduce variability and noise. The data was also filtered by the day of week and the time of day in some cases to account for building occupancy and RTU scheduling. The same methodology was used in both baseline and post-installation cases to be consistent.

Since both pre and post-implementation data were collected for limited measurement periods, a weather-normalized savings method was used to estimate the annual energy consumption of the RTUs. In the normalized savings method, the annual energy savings are determined by subtracting adjusted post-installation energy usage from the adjusted baseline usage. Therefore, the method requires mathematical models to adjust measured data. In this study, models were developed using empirical relationship between RTU energy use and outside air temperature, an independent variable, in accordance with M&V guideline (ASHRAE, 2014). The models were then adjusted using typical NOAA ambient temperature data to determine normalized annual savings under TMY3 conditions.

Model uncertainty was measured by coefficient of determination ($R^2$) and coefficient of variation of the root mean squared error (CV-RMSE). For each site, avoided energy use and normalized savings estimates and their uncertainties were calculated to evaluate the goodness of fit.

## SITE 1

As previously mentioned, each heat pump was independently controlled to provide heating or cooling to the building. Only HP-2 and HP-3 served the same zone and therefore the customer tried to keep the two independent thermostats with the same setpoint during baseline period. As expected, the baseline data showed that heat pumps mostly operated in heating mode in the morning to warm up the building and in cooling mode in the afternoon. As shown in Figure 5, heat pumps turned on at around 7 AM to heat the space until the 68°F setpoint was reached. During the afternoon, the heat pumps frequently cycled on and off to keep the 74°F setpoint. Note that HP-5 and HP-6 had the thermostats set in “fan auto” mode. In this mode, the fan is turned on only when there is a demand for cooling or heating, but otherwise turned off. This operating mode is commonly used in residential HVAC, but not a preferable method in commercial spaces because it does not provide adequate ventilation to the space. However, because this was the customer’s preferred setting, the mode was not changed in the post installation to have a fair comparison.

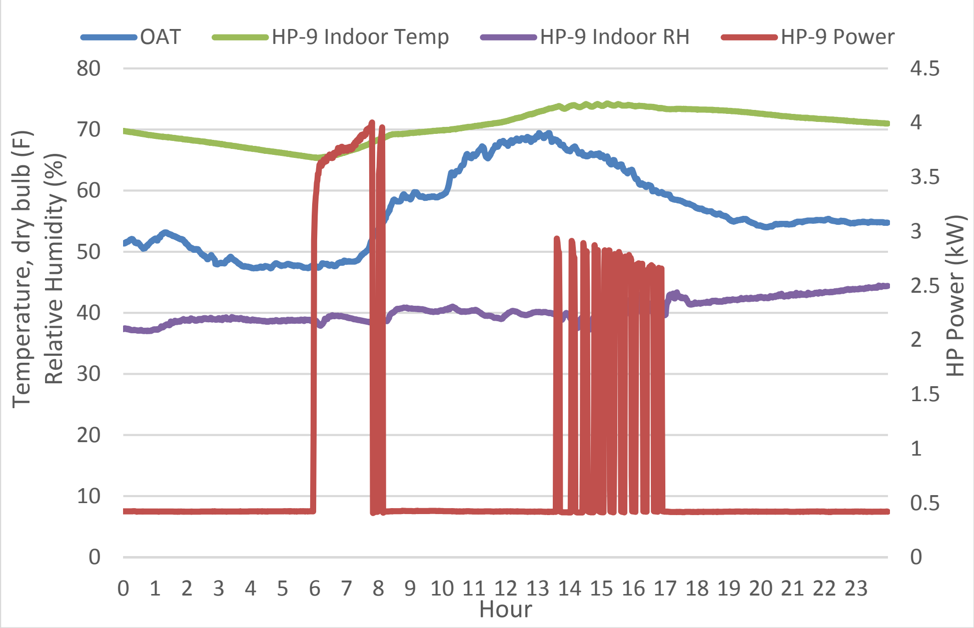

**FIGURE 5: TYPICAL BASELINE UNIT OPERATION**

Figure 6 shows that the heat pumps turned on briefly in the morning to heat the building after the ET was implemented. The operational difference is clearly visible in the afternoon, where the amount of cycling is reduced drastically. Additionally, the scheduling was improved by slightly delaying the morning warm up and shutting off the units at 5PM to match the building occupancy.

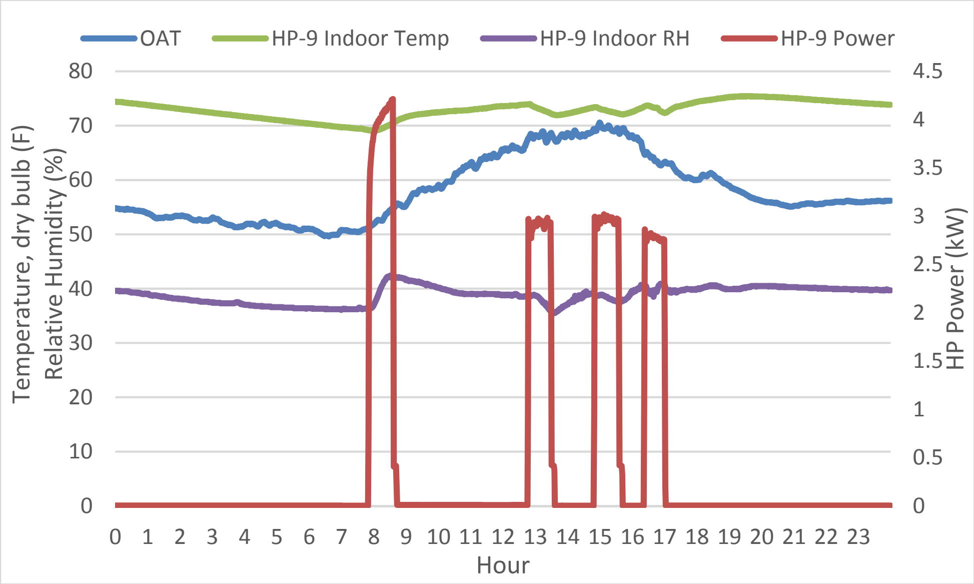

**FIGURE 6: TYPICAL POST-RETROFIT UNIT OPERATION**

Several attempts were made to create a model using regression analysis, but acceptable accuracy was not achieved for both baseline and retrofit periods due to general lack of data points, lack of post-retrofit data points in the high temperature range above 75°F, and irregular baseline operation during holidays. The efforts included analysis using different independent variables, multiple variables, inferred the building heating/cooling balance point from our scatter plots. Figure 7 below shows one of regression analysis performed for the total hourly energy consumption of six heat pumps.

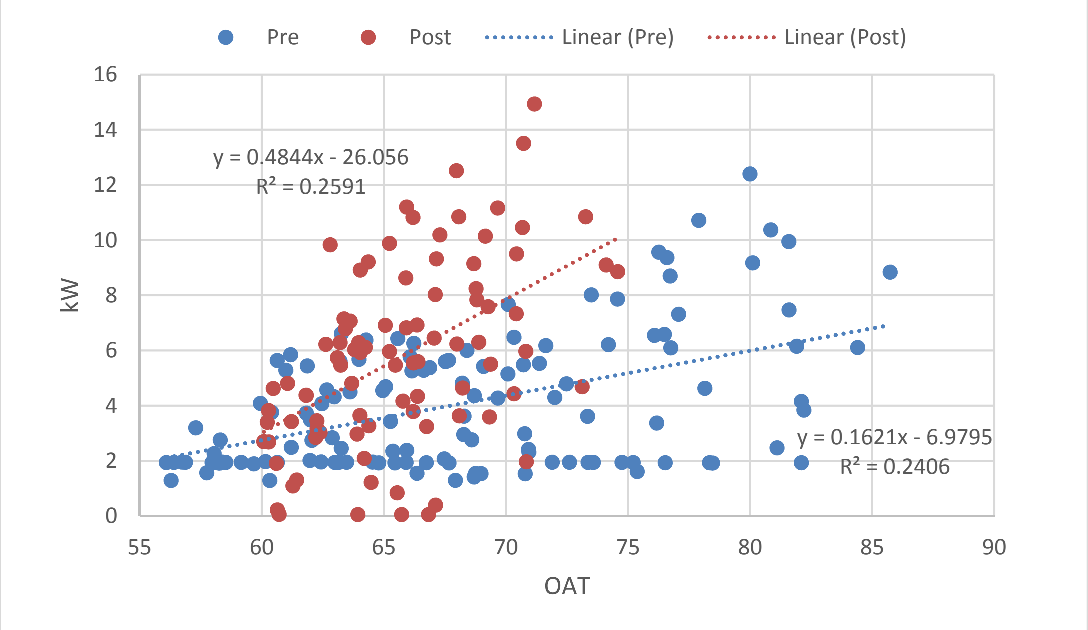

FIGURE 7: REGRESSION ANALYSIS MADE FOR TOTAL POWER CONSUMPTION OF SIX HEAT PUMPS DURING OCCUPIED PERIODS

## SITE 2

At the second site, the power consumption of ten AC units and zone conditions were monitored for two months during baseline and seven months during post-retrofit. Since the satisfactory models could not be developed for site 1, the data were collected for prolonged durations. Of ten AC units, one of the AC units (AC-10) was removed from the analysis because the logged data showed erratic behavior and it was later determined that the sensors had been defective.

At this site, the thermostats were not programmed for scheduling or night setback. The fans were also set to be always on for some units. Thus, all RTUs operated 24/7. Figure 8 below represents the typical operation of a baseline unit, which shows the unit fan operated continuously drawing about three amps and the compressor cycled on and off throughout the day to keep the indoor temperature at 72°F.

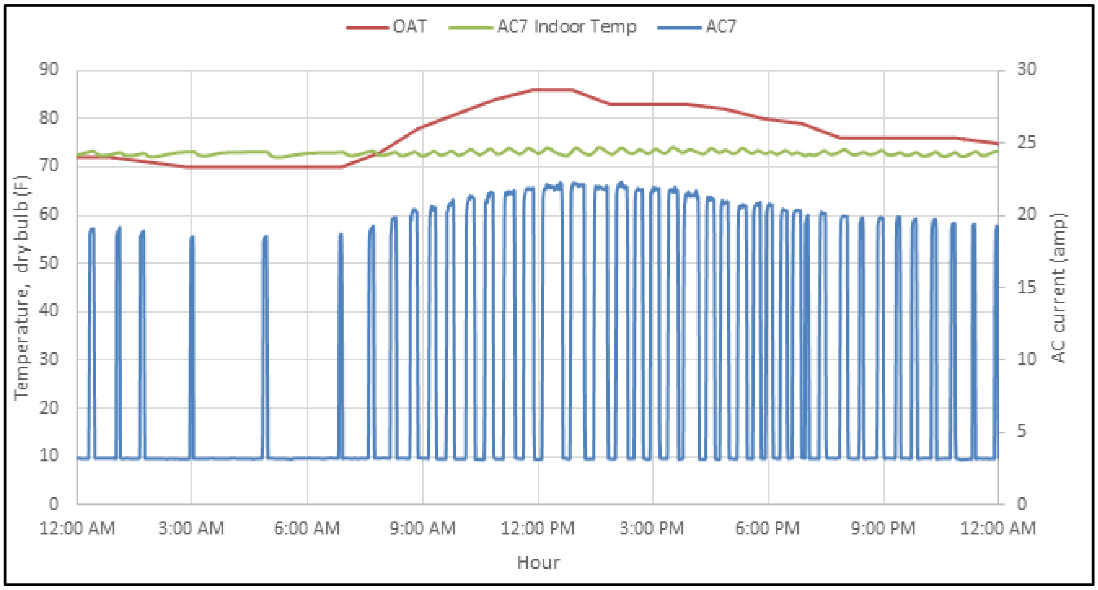

FIGURE 8: TYPICAL BASELINE UNIT OPERATION

Figure 9 below shows the typical operation of the same retrofitted unit during a weekday. After the retrofit, RTUs were scheduled to turn on only during occupied period from 6AM to 7PM. The zero-power draw at night indicates that scheduling was successfully implemented to reduce both fan and compressor run hours. Additionally, the number of compressor cycling during the occupied period was clearly reduced.

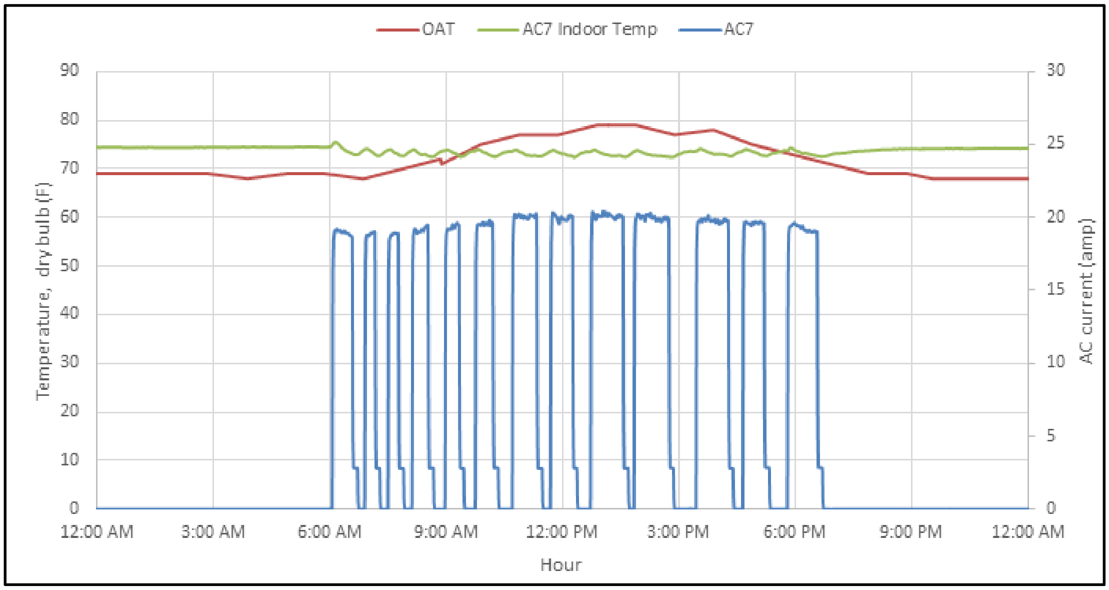

FIGURE 9: TYPICAL POST-RETROFIT UNIT OPERATION

To assess energy savings, the energy consumptions of nine AC units were compared before and after the retrofit. Per the appropriate normalized savings method, regression analysis was performed against outside air temperature. For this analysis, the energy consumption of the RTUs during unoccupied period was disregarded because the RTUs were scheduled to be turned off. No other data filtering was performed as they did not improve the uncertainty. The resultant models showed a slight increase of post-retrofit energy consumption during operational hours. This was shown to be caused by both unusually humid conditions as well as comfort improvements that applied only to the retrofit period. Further details will be discussed in the following sections.

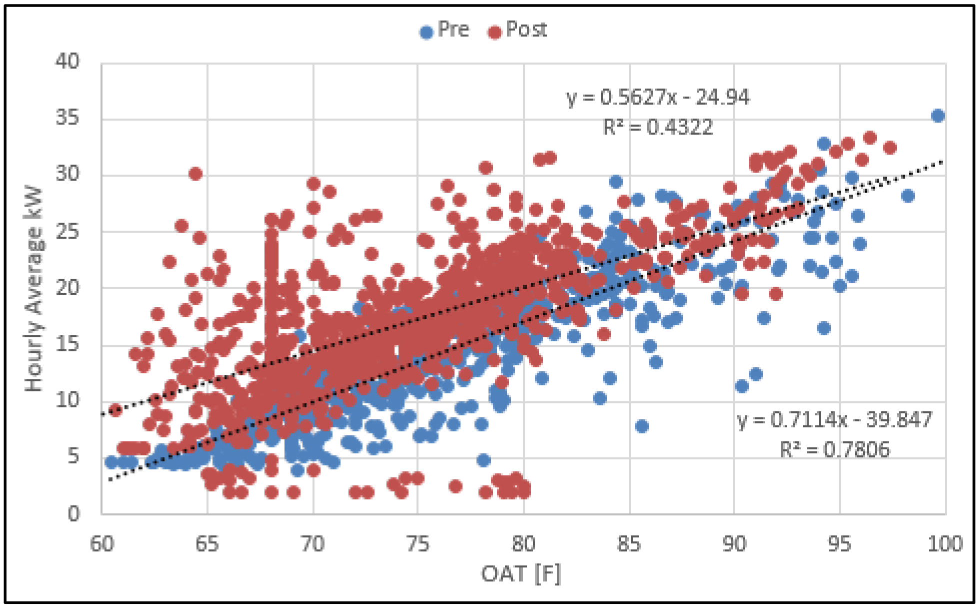

FIGURE 10: REGRESSION ANALYSIS MADE FOR TOTAL POWER CONSUMPTION OF NINE AC UNITS DURING OCCUPIED PERIODS

# RESULTS

M&V results obtained from the two test sites are detailed in the following four categories: Thermal Comfort, Compressor Cycling, Energy Savings, and Demand Reduction.

## THERMAL COMFORT

The algorithm proposed by the vendor utilized not only dry-bulb temperature but also relative humidity, radiant heat, and other factors relevant to human comfort to determine heating or cooling demand in an effort to improve thermal comfort in a zone.

The green shaded area in the psychrometric chart below represents the summer comfort zone set by ASHRAE Standard 55. Thermal comfort is determined by the combination of dry-bulb temperature and humidity. For example, thermal comfort can be met even when space temperature is raised up to 80°F, if the relative humidity is kept between 20% and 60%.

Dry-bulb temperature and humidity data were collected in each zone and their hourly averages were plotted in a psychrometric chart. The figures below are for only one of the building zones, but the data are typical of the other zones as well. Figure 11 displays data points outside of the green shaded area, or thermal comfort zone, even though the temperature was maintained at or below 72°F setpoint indicating that thermal comfort was not met during baseline periods at Site 1. On the other hand, the post-retrofit data shows that the space conditions were maintained within thermal comfort limits. These include times when the dry-bulb temperature exceeded the 72°F setpoint because the low humidity condition in the zone allowed the space temperature to drift up. Since the compressor only responds to the dry-bulb temperature, the retrofit resulted in reduced compressor run hours and energy savings.

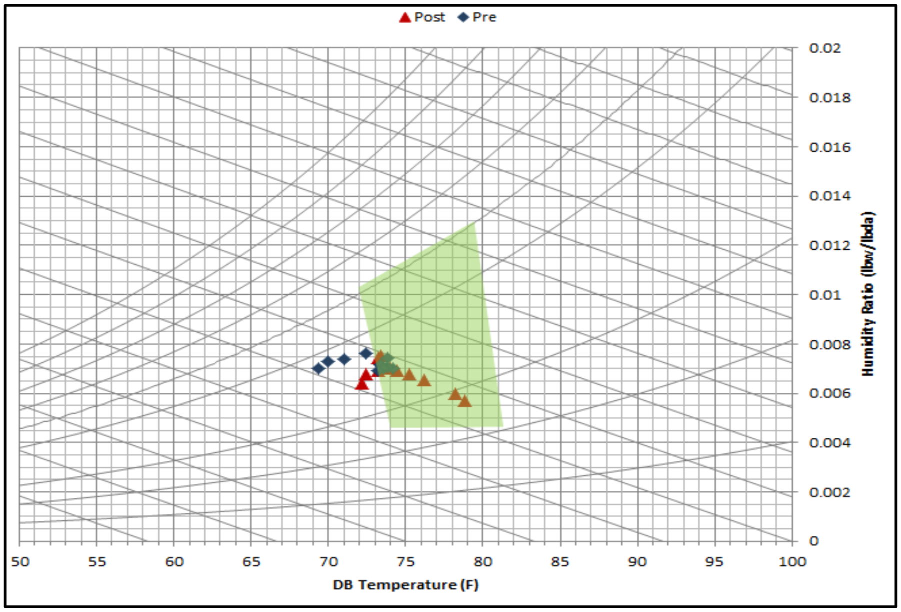

FIGURE 11: SITE 1 PRE AND POST CONDITIONS

At site 2, the ET was also able to achieve improved thermal comfort. However, the effort to increase thermal comfort resulted in an increase in energy consumptions for several reasons. First, the San Diego region experienced unusually humid weather conditions during post-retrofit measurement periods. Therefore, meeting thermal comfort required an increase in total enthalpy removed from outside air as compared to baseline conditions. Secondly, the customer survey revealed that the setpoint was frequently changed after the retrofit. The usability of the ET allowed the maintenance personnel to readily modify setpoint whenever requested by the occupants. As a result, the space temperature was not able to drift to a higher temperature as much as was originally expected.

Figure 12 shows how the humidity was lowered during the post installation period even if the outside air humidity was actually higher. The post-retrofit hourly average data around 77-79F represents the system's default control target that was subsequently overridden by the users in favor of setpoints between 72-75F.

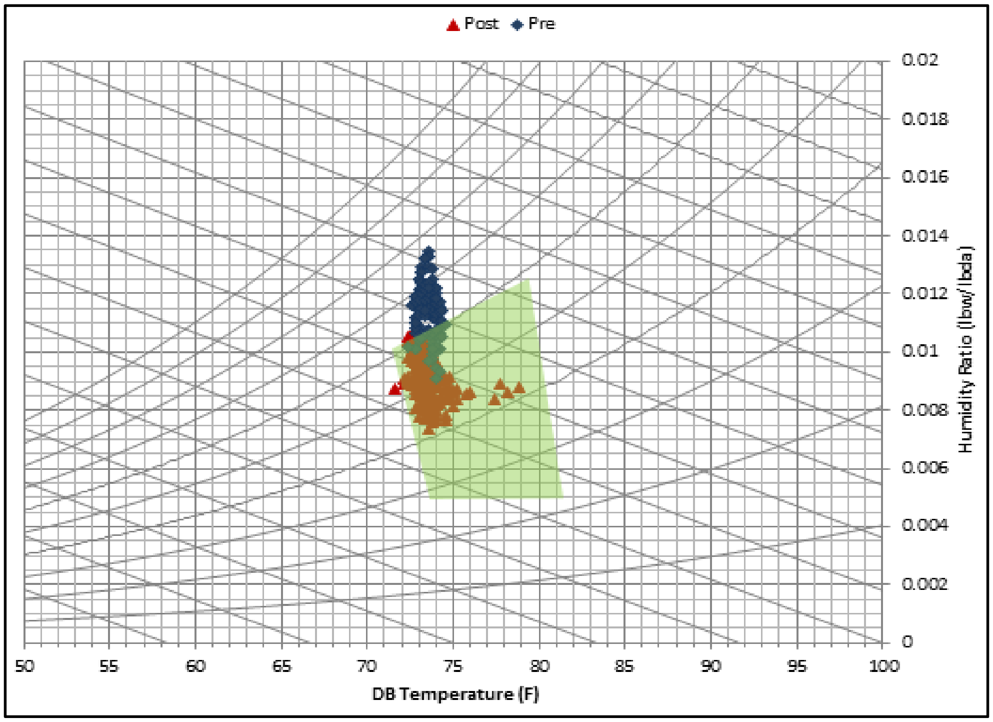

FIGURE 12: SITE 2 ZONE 6 PRE AND POST INDOOR CONDITIONS

## COMPRESSOR CYCLING

An additional benefit of the installed controls, although not its primary objective, is the reduction of compressor cycling. Figure 5 and Figure 6 illustrated that the cycling frequency was reduced after the ET retrofit at Site 1. During the baseline, the heat pump compressor cycled on and off approximately 10 times in less than four hours. The operational improvement is evident in the post-installation data, where the compressors cycling frequency was reduced greatly.

At the second site, the AC units were not scheduled before the ET retrofit and therefore ran continuously. Figure 13 below shows the AC units were on 24/7 to keep the zone temperature setpoint and the compressors cycled on and off frequently. The number of compressor cycling was greatly reduced post-retrofit. Note how the indoor temperature was let float during the unoccupied hours.

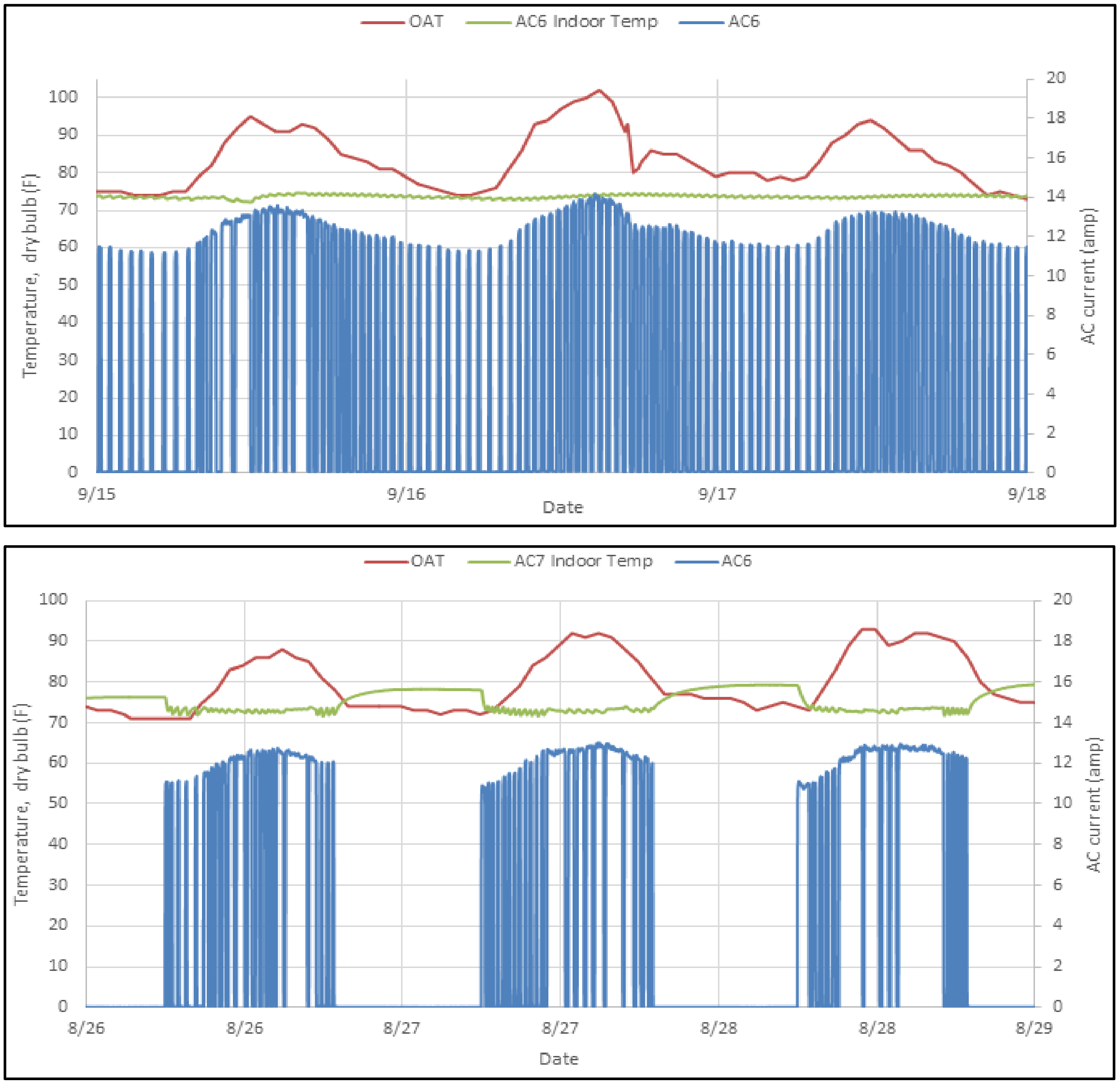

FIGURE 13: SITE 2 PRE AND POST INSTALLATION AC-6

## ENERGY SAVINGS

Limited data were collected at the first site due to the specific operations. Therefore, regression models were not attainable with acceptable accuracy for both baseline and retrofit periods. However, pre- and post-retrofit heat pump operations of two similar days were compared as shown in Figure 14 and a few energy saving features were noted, under comparable outside conditions:

- The compressor and fan run times during unoccupied hours were reduced by improving scheduling.
- The amount of heating consumption in the morning warm up was reduced.
- The overall energy consumption in cooling mode was reduced.

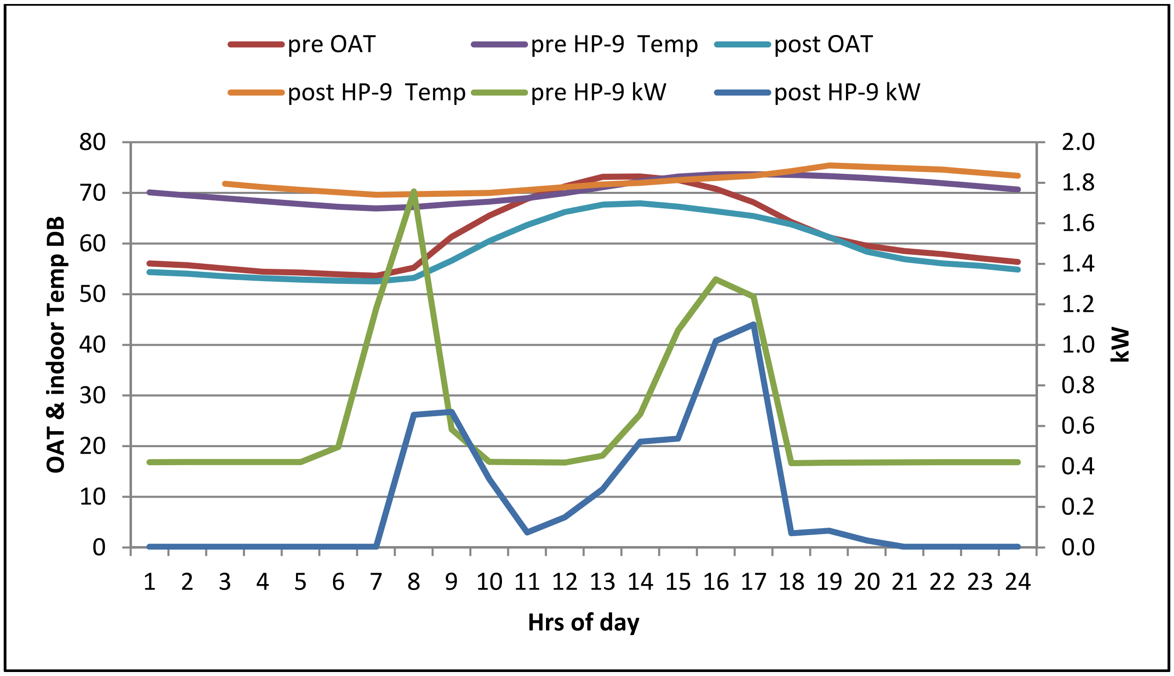

FIGURE 14: PRE- AND POST-RETROFIT COMPARISON

To quantify the energy savings, the daily energy consumptions of six heat pumps were compared by selecting two pre- and post-retrofit days with similar ambient conditions. As Figure 15 below shows, five of six heat pumps evaluated in this study exhibited savings. The combined savings for the six units represents 29% of baseline energy consumption. The result did not show significant demand reduction during the 12PM to 6PM peak period.

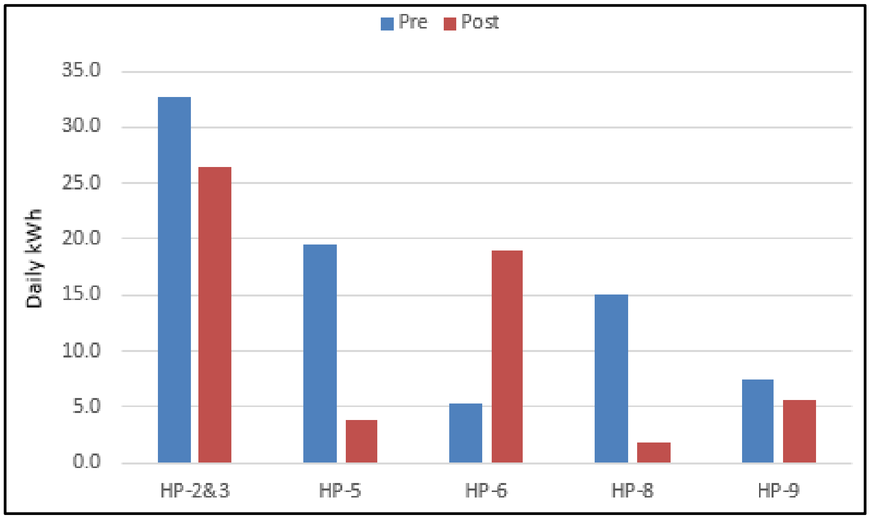

FIGURE 15: DAILY AVERAGE ENERGY CONSUMPTIONS OF SIX HEAT PUMPS

At site 2, the energy savings were calculated using the regression analysis results with NOAA meteorological data for San Diego. Figure 16 illustrates the modeled hourly energy use for baseline and post-retrofit cases for the entire year. The resulting savings for the nine units represented 38% of the baseline energy consumption. Table 7 below summarizes the energy savings achieved at each site.

TABLE 7: ESTIMATED ANNUAL ENERGY SAVINGS PER SITE

| | Baseline kWh | Retrofit kWh | Savings kWh | % Savings |
|---|---|---|---|---|
| **Site 1** | NA | NA | NA | 29% |
| **Site 2** | 57,900 | 35,900 | 22,100 | 38% |

Figure 16 illustrates the modeled hourly energy use for baseline and post-retrofit cases for the entire year for Site 2. The hourly energy consumption of nine AC units during the occupied periods increased slightly in post-retrofit, especially at low outside air temperature range. This increase in energy consumption can be explained by change in RTU operations. In baseline, RTUs were on all the time and therefore the compressors ran under steady state condition even during the night when the building was not occupied. After the retrofit, however, RTUs were scheduled to shut off at the end of business hours. Since the RTUs didn't operate at night, the thermal load accumulated in the building until the units turned on in the morning. This caused the AC compressors to run more in the morning until the load accumulated during the night was satisfied, and the building reached the steady state condition.

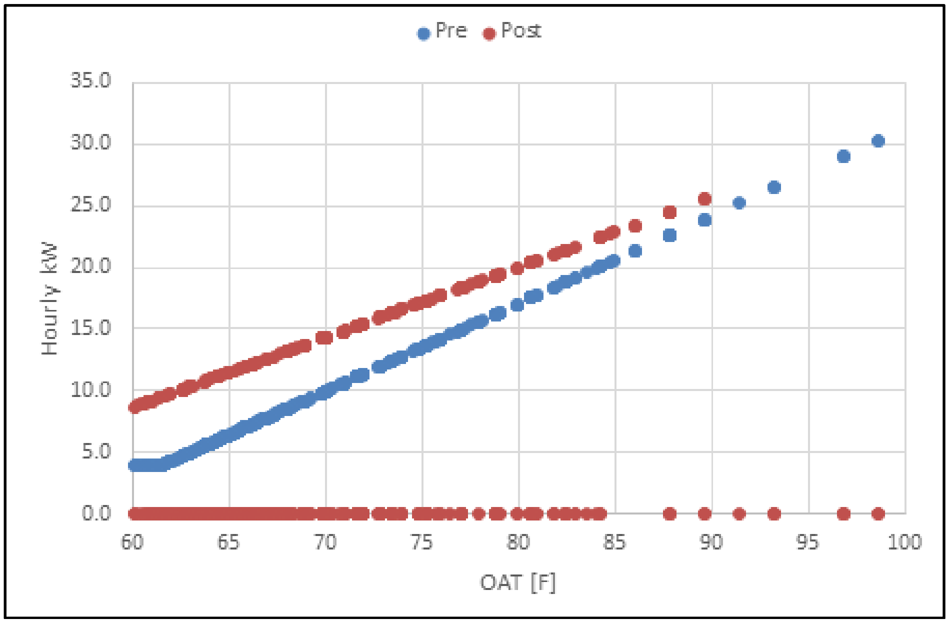

FIGURE 16: NORMALIZED PRE AND POST MODELS OBTAINED FROM REGRESSION ANALYSIS IN FIGURE 8

The average daily energy consumptions of nine RTUs during weekday were also compared and shown in Figure 17 below. All units showed energy savings from the ET implementation. However, the majority of savings come from scheduling the units or shutting the units off during unoccupied periods.

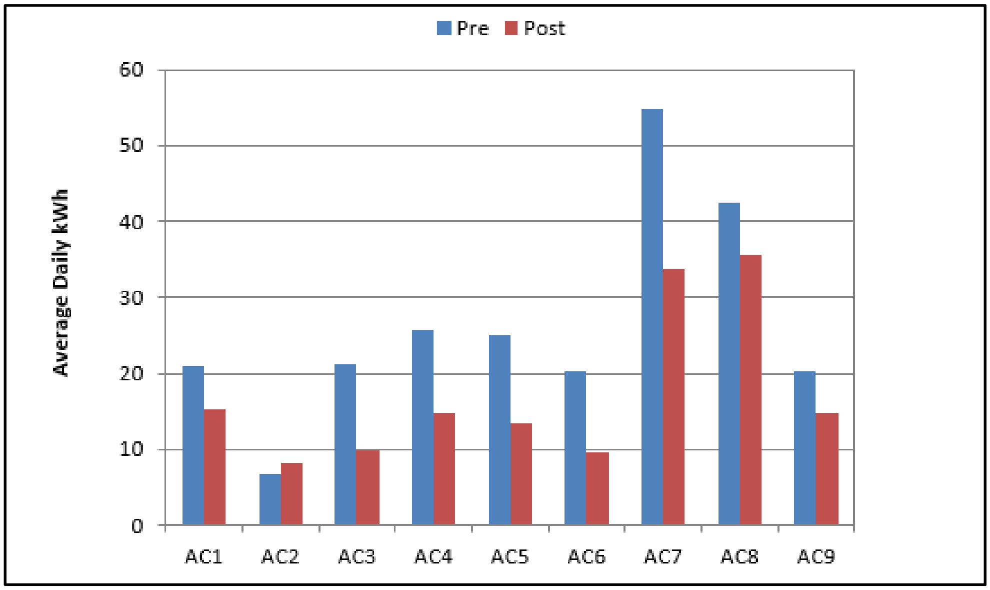

**FIGURE 17:** AVERAGE DAILY CONSUMPTIONS OF NINE AC UNITS

As Title 24 requires seven-day programmable thermostats on unitary systems, the savings achieved from scheduling will not be eligible for utility program incentive. Therefore, energy savings that occurred during occupied periods were evaluated by comparing the pre- and post-retrofit energy consumptions of the nine AC units between 6AM and 6PM. Of nine units, daily average consumptions of six AC units increased when the energy consumptions were compared only during occupied periods. Overall, the total daily average energy consumption of the facility increased from 166 kWh per day to 173 kWh per day.

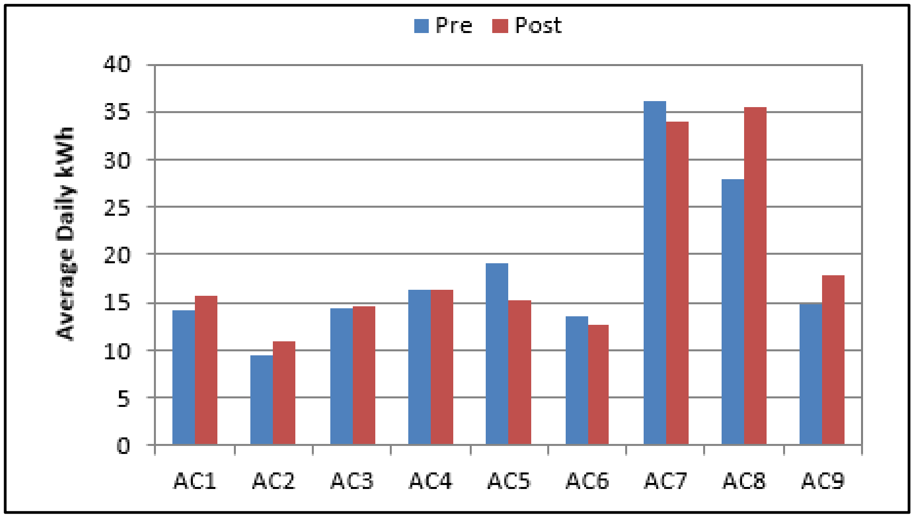

**FIGURE 18:** AVERAGE DAILY CONSUMPTIONS OF NINE AC UNITS DURING OCCUPIED PERIOD

One of the major reasons for the increase in unit energy consumption is due to difference in outside weather conditions between baseline and post-retrofit periods. In the summer of 2015, San Diego region experienced above average humidity levels due to El Niño (a weather phenomenon caused by unusually warm water of the western Pacific Ocean flowing eastward), which coincided with the post-retrofit measurement period. Figure 19 is the plot of outside air conditions during baseline and post-retrofit measurements periods on a psychrometric chart. It is evident from the chart that outside air contained more moisture during the post-retrofit measurement period, especially at high dry-bulb temperatures.

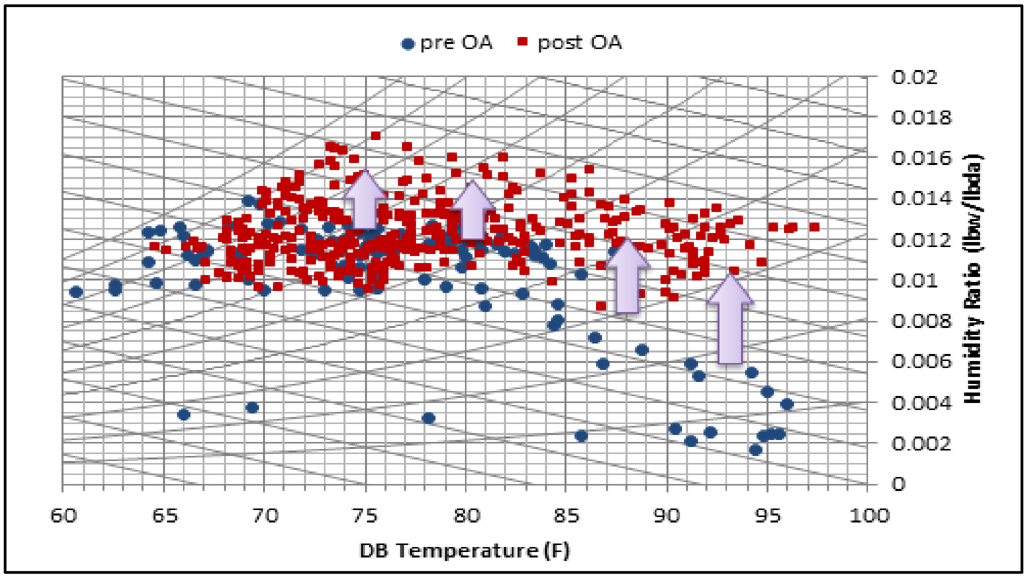

**FIGURE 19: PRE AND POST OAT CONDITIONS ON PSYCHROMETRIC CHART**

To examine the effect of outside air humidity, the differences in enthalpies between outside air and the conditioned indoor air (Δh) were calculated and compared. As previously mentioned, NOAA weather data was used to calculate the hourly average enthalpy of outside air. The hourly average enthalpy of indoor air was calculated for each zone, using measured data including zone air temperature and relative humidity. The Δh was then plotted with respect to outside air temperature (dry-bulb) and regression models were created. The resulting Figure 20 below shows that Δh is greater during post-retrofit measurement period, especially at high outside air temperatures.

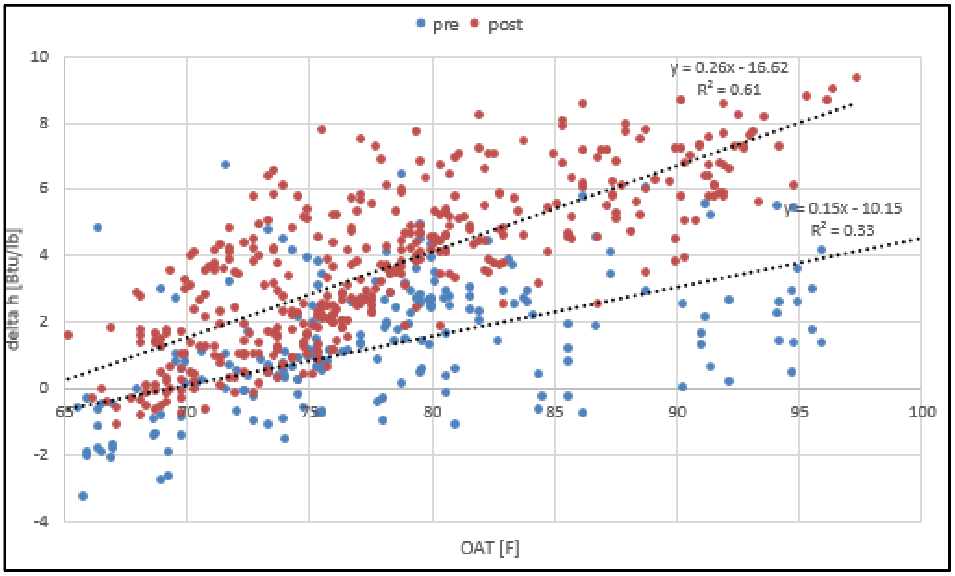

**FIGURE 20: THE ENTHALPY DIFFERENCE BETWEEN INDOOR AND OUTSIDE AIR AS FUNCTION OF OUTSIDE AIR TEMPERATURE**

The increase in $\Delta h$ translates into compressor load increase. To account for this increase in the load, the baseline was adjusted up to match the post-retrofit load. Per the Statewide Customized Retrofit Offering Procedures Manual, the energy savings are calculated using post-retrofit equipment load:

$$Energy\ Savings = \sum \left( \eta_{pre} - \eta_{post} \right) \cdot Q_{post} = \eta_{pre} \cdot Q_{post} - kWh_{post}$$

Where

$\eta_{pre}$ = efficiency of baseline equipment (kW/$\Delta$h)

$\eta_{post}$ = efficiency of equipment after the retrofit

$Q_{post}$ = equipment load after the retrofit ($\Delta h_{post}$)

$kWh_{post}$ = post-retrofit energy consumption

Annual hourly post-retrofit loads ($\Delta h_{post}$) were modeled using the regression coefficients obtained from Figure 20 and NOAA meteorological data for San Diego. The efficiency of baseline equipment was deduced from the combination of previously modeled baseline energy consumption (unadjusted) and the modeled pre-retrofit loads. Using the above equation, the hourly baseline consumption was adjusted by multiplying the calculated baseline efficiency and the post-retrofit loads. No change was made to the modeled hourly post-retrofit consumptions. The above adjustments resulted in overall increase in the baseline consumption during occupied periods and yielded 8% savings. The results of the so adjusted savings calculation are summarized in Table 8 below.

TABLE 8: ESTIMATED ANNUAL ENERGY SAVINGS WITH ENTHALPY ADJUSTMENT AT SITE 2

| | Baseline kWh | Retrofit kWh | Savings kWh | % Savings |
|---|---|---|---|---|
| **All hours** | 83,800 | 35,900 | 47,900 | 57% |
| **Occupied hours only** | 38,200 | 35,200 | 3,000 | 8% |

## DEMAND REDUCTION AND DEMAND RESPONSE

Demand reduction was not observed during the initial testing because the demand limiting feature of the ET was turned off by the vendor. This was done so that the energy savings from the other control features can be isolated from the demand reduction. A separate testing was conducted on May 30th, 2014 at test site 1 and on September 25th, 2015 at test site 2 to demonstrate the permanent demand reduction and demand response capabilities of this technology.

### SITE 1

At test site 1, all units except for HP1 were tested for permanent demand reduction. The heat pumps were programmed to operate below a maximum power setpoint, which was set at the total demand of 16 kW per hour or approximately 65% of facility HVAC peak load. In this testing, three units were allowed to run concurrently at full capacity. The units were rotated so that each zone would receive cooling, but the overall consumption of all units at any one point in time would stay below 16 kW. Figure 21 below shows the ET successfully implemented demand reduction after 12:30 PM, which was when the test was initiated.

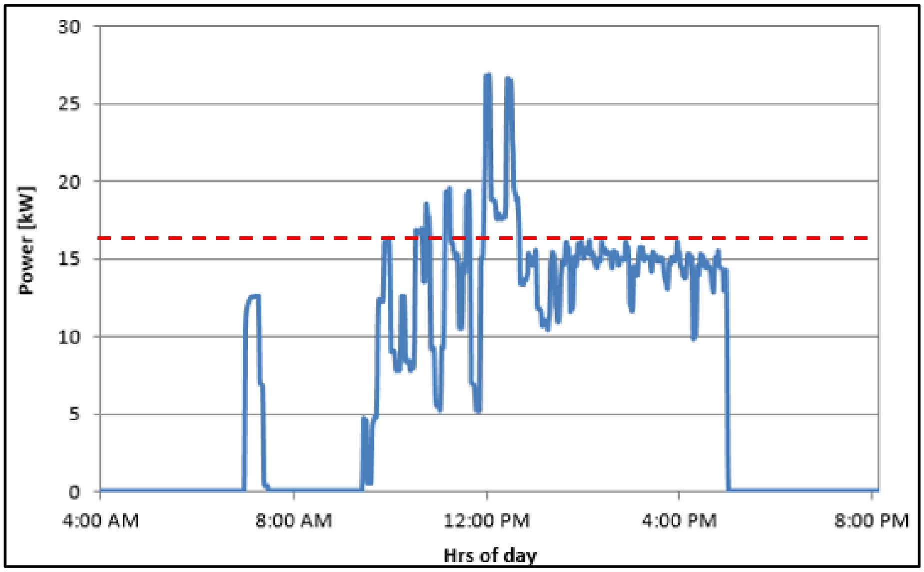

FIGURE 21: DEMAND REDUCTION TESTING AT SITE 1

## SITE 2

At test site 2, all units except for AC10 were controlled to operate under a demand limit, which was set at 70% of full capacity beginning at 10:30am for permanent demand reduction purposes and at 50% beginning at 3:30pm for demand response purposes. At 4:30pm, the system was set back to 70%. The testing was concluded at 6pm when the building's occupancy schedule ended. Figure 22 below shows that total power demands were kept within the pre-programmed limits for the duration of the test.

The 50% demand reduction was kept only for an hour period. During the hour, the average indoor air temperature started to increase slightly (~1°F), indicating that the zone loads were not completely satisfied. This reaction is typical for demand response events.

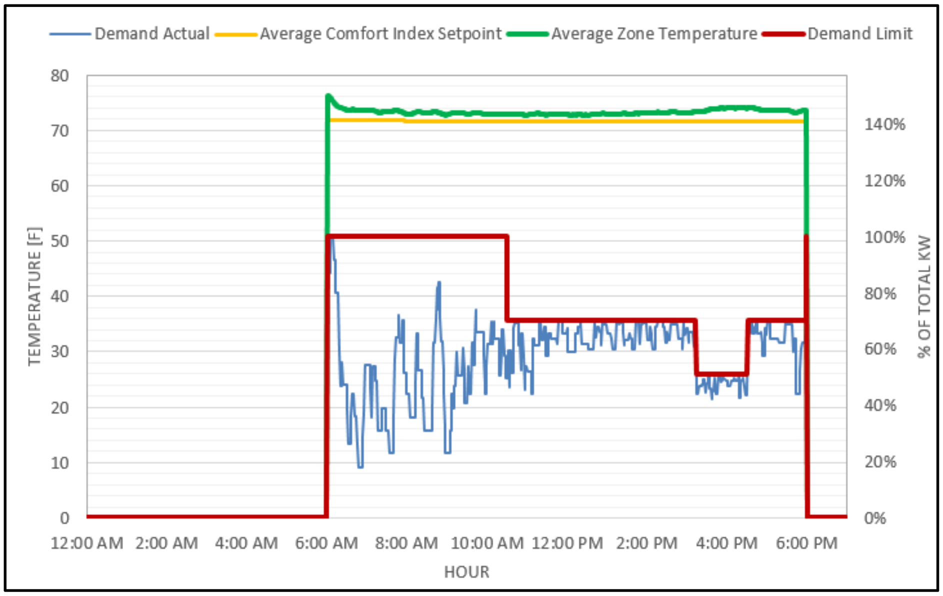

FIGURE 22: DEMAND REDUCTION TESTING AT SITE 2

# DISCUSSION

The M&V results showed that the installed ET at two sites both succeeded its objectives to increase occupant comfort, to reduce compressor cycling, and to reduce energy and demand. The following sections discuss the functionality and the plausibility of the ET based on the results.

## CUSTOMER FEEDBACK

The vendor and the consultant conducted a survey at each test site and received feedback from the customers. Overall, the customers liked the new thermostats and the “app like” feel of the web interface, which allowed them to adjust schedules, setpoints, and other parameters as needed. The fact that the customers desired to keep the new system in place at both sites is a testimony to their satisfaction. The customers were especially pleased at the first site, where each occupant was given his/her own control and was able to access the settings online. The improvement in the zone comfort was also noted by the occupants.

At the second site, both compliments and complaints were filed during the survey. Overall, the occupants confirmed the increase in comfort due to less humidity. Some customers saw the technology survey as an opportunity to complain about the HVAC system in general, which is a common behavior found in this type of survey. A few complaints were made about experiencing discomfort at the second site. However, they are believed to be related to the problem with existing HVAC system configuration rather than with the studied technology. For example, the air conditioning of five separate offices is controlled by one thermostat located in one of the offices. The discomfort experienced by the occupant in one of these offices is not because of the installed technology, but is likely due to the lack of thermostat and the HVAC system configuration. It should also be noted that there were several mechanical failures not related to ET, which were not addressed immediately by the facility management. Since the technology vendor was often present at the site due to the ongoing test, they were usually the first to be suspected for causing any mechanical issues even when the root cause was later identified to be an unrelated to the test. This may also have biased survey responses somewhat negatively.

## UTILITY ENERGY INCENTIVES

There are several types of smart thermostats, which are already incentivized by the California utilities. In SDG&E territory, a smart thermostat is incentivized in midstream program.

The current Title 24 code requires seven-day programmable thermostats. As such, the energy savings from shutting off the units at night and during the weekend are not eligible for utility incentive programs. However, the energy savings resulting from the ET’s other features such as controlling the unit based on a comfort factor, the cycling of the compressor, and the demand limiting would be all eligible for incentives.

The ET is OpenADR 2.0a compliant and capable of managing multiple RTUs to reduce the facility peak demand. Thus, the author believes that the ET would best fit in the utility’s Automated Demand Response Program and/or Custom Incentive Program for demand reduction for its capability to do demand response while also providing the customer with energy efficiency and permanent peak demand reduction. Further analysis by the utility should be conducted to decide where the product best fits within the incentive programs.

## MARKET BARRIERS

While it is premature to make any assumptions regarding the market penetration of the studied technology, it is appropriate to state that it could serve an important share of the HVAC market. One of market barriers of promoting proposed technology is lack of consumer knowledge. Customers have difficulties choosing the right product for their building's HVAC needs because there are many varieties of products in the market. The lack of information and knowledge about the products and technologies often lead consumers to select the one that requires the least initial cost, which might not necessary be the least expensive option in the long run. The proposed technology costs approximately $350 per zone including thermostats, controllers, and installation. The payback of the system varies widely depending on the facility and whether or not the units are currently running all the time or have a schedule. Additionally, the payback depends from the contribution of utility incentives that often pay by the energy saved (kWh), the permanent demand reduction (kW), and the demand response peak reduction (kW). AESC calculated that the payback could go from 8 years for customers that have already tight equipment scheduling and whose building is located in a utility territory that does not provide incentives to 3 years for customers that would have higher savings due to lack of scheduling and whose building is located in a utility territory with high incentives.

## POSSIBLE RISKS

It will be important to distinguish the permanent load reduction and the demand response capabilities of this technology. The demand reduction results showed demand limiting feature of the system works as designed with relatively moderate settings. At both sites, the total HVAC demand was reduced by 30%-35% with no effect to the zone conditions. With more aggressive settings, demand control can bring additional energy savings. However, the extent of reduction should be carefully selected to avoid causing occupant discomfort. At site 2, for instance, the indoor air temperature started to deviate from the setpoint when the total HVAC demand was reduced by 50%. The feasible amount of reduction without jeopardizing occupant comfort may differ from facility to facility depending on their load characteristics and trial and error approach may be required to find the appropriate limit.

The evaluator did not see any specific technology risks associated with the installation.

## POSSIBLE FUTURE STUDY

Both studied installations, while successful, had some characteristics that deviated from a typical office building. The first building included a manufacturing space with a storage room. Additionally, some heat pumps were programmed with fans in the "auto" mode, which is atypical for a commercial building due to ventilation risks. The second site also had issues with existing HVAC configurations including unscheduled thermostats, poor air distribution, and unmatched zoning due to facility changes over time. Additionally, the baseline data required adjustment because M&V was performed over the span of two summer seasons and the weather conditions changed dramatically during that period. To obtain more reliable results, a future study is recommended in an office with more consistent zoning and programmable thermostats.

Such future study should be performed preferably within a single season, in a week-on, week-off manner, to minimize the risk of successful data normalization and need for correction.

Another possible future study could involve measuring and quantifying the thermal comfort of occupants. For a while now, the air conditioning industry has been talking about different ways to evaluate occupant comfort beyond the dry-bulb. However, only a few products have arrived in the market place due to its difficulty to quantify the occupant comfort. Further experiments and surveys to measure thermal comfort from the perspective of occupant themselves can potentially lead to additional energy savings opportunities and improved user acceptance.

# CONCLUSION

The implementation of this HVAC management system with dynamic energy and demand reduction optimization achieved an increase in zone thermal comfort and reduction in compressor cycling. Additionally, the advanced scheduling and the innovative comfort setpoint were able to reduce the energy consumption.

During demand reduction testing, the system was able to reduce HVAC-wide peak demand to the set limit of 50% of the maximum HVAC peak capacity with an increase of average zone temperature of only 1°F. The system was able to reduce HVAC-wide peak demand by 30% with *no impact* to average zone temperature. It is likely that these results hold during most of the year except on design days. This makes for a significant year-round demand cost savings opportunity that is independent of demand response program participation.

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