Controllers for DX HVAC Units

San Diego Gas & Electric
Emerging Technologies Program
Technology Assessment Draft Summary

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EXECUTIVE SUMMARY

In support of California's strategic plan to accelerate the penetration of energy efficiency technologies, San Diego Gas & Electric's Emerging Technology program funded a study of two controllers for DX HVAC units at two office buildings. The primary goals for this project were to determine the energy savings potential of two similar but different controllers for packaged units. To gain insight into the technology, a field test and subsequent analysis were conducted.

The field test was conducted over a two-year span, with phase 1 test conducted at two office buildings in SDG&E territory and phase 2 continued at one of the sites. The analysis of data collected after the phase 1 test showed that neither controller saved energy at the two test sites. A few uncontrolled factors, such as occupancy level and thermostat setpoint changes, were considered as possible culprits. Therefore, phase 2 testing was conducted with a few modifications, including the addition of extra temperature sensors, longer monitoring periods, and alternating the baseline and post scenarios every couple of weeks to reduce any variability to the building occupancy that might have caused the lack of savings during the first phase. The following summarizes the scope of each phase:

Phase 1 – The measures were implemented at two office buildings in San Diego area. The office building located in El Cajon was served by total of eleven 3-ton wall mounted packaged units. Of the eleven units, five units were retrofitted with controller A and additional five units were retrofitted with controller B. In the other office building, located in Poway, the controllers were installed on the total of ten rooftop units with the total cooling capacity of 34 tons. The unit size ranged from two to six tons and the units are between two and three years old. Similar to the other site, controller A was installed on five rooftop units and controller B was installed on other five units. Data were collected using logging instrumentation for over a period of 12 weeks, approximately six weeks for establishing a baseline and another six weeks for collecting data after the technology implementation.

Phase 2 – The phase 2 field test was sustained at the office building in Poway. Three more units were added to the test, making the total number of units to 13. Of the 13 units, eight units were retrofitted with controller A and the rest were retrofitted with controller B. Three additional temperature sensors were added to each unit so that cooling load could be calculated directly. Data were collected for a period of 18 weeks. During this test, the controllers were turned on and off every two weeks.

Although the phase 2 data greatly improved statistical significance of regression models developed, the savings calculated from the models were still one to two percent of annual total usage. It was concluded that while the controllers had potential to save energy when fittingly installed in certain applications, the technology is not ready to be implemented in packaged rooftop units in small to medium commercial buildings in SDG&E territory.

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INTRODUCTION AND BACKGROUND

This study was performed by Alternative Energy Systems Consulting (AESC) on behalf of San Diego Gas and Electric's (SDG&E) Emerging Technologies (ET) program. The ET program strives to increase the exposure and success of emerging and underutilized energy efficiency and demand side management technologies in California. AESC is an energy engineering consultancy specializing in utility programs, technology assessments, and measurement and verification (M&V). This field test was performed in order to study the effects and benefits of two controllers aimed at optimizing the performance of existing small DX HVAC units (less than 20 ton) including packaged, split, heat pumps, and window units that uses the vapor compressor cycle to provide cooling and/or heating.

Despite the massive energy consumption of these widely-used HVAC equipment types, efficiency measures for unitary HVAC units have struggled to gain market traction, particularly for retrofit applications due to various market barriers. Energy efficiency efforts have largely focused on improving design point efficiency and function of new HVAC units; however, the large existing RTU base is a prime target for improved energy efficiency at part load conditions.

TARGET MARKET AND SETTING

DX HVAC units are very often used in standalone retail, education, restaurant, and small to medium size office buildings. Among other reasons, small DX HVAC units have this market dominance in small and medium commercial buildings because they require little site-specific design, can be dropped into position for space conditioning expansion or equipment replacement without impacting the remainder of the building, do not require auxiliary systems, require relatively little commissioning, and any downtime will impact only one zone rather than an entire building.

Small DX HVAC units are essentially a collection of all necessary heating, cooling, and ventilation components including compressors, supply fan, air dampers, condenser, refrigerant coils, and a gas furnace or heat pump function if the unit is also used for heating. Although there is often airflow interaction between zones through doorways, halls, and open spaces, units typically serve a single zone and are controlled by a single thermostat. These thermostats can be programmable or smart thermostats with features such as scheduling, setpoint setbacks, occupancy sensors, and remote control in some cases. However, many units are still controlled by analog or pneumatic thermostats and even programmable thermostats can easily become out of sync with occupancy patterns or be improperly programmed.

DX HVAC units have an estimated average lifespan of 15 years (DOE, 2012) and many existing and smaller size units in the marketplace do not have controls that meet recent California code revisions. The 2016 Title 24 building standards require new air-cooled package units and heat pumps to be at least 9.5 to 11.2 EER (depending on the size and type) and be controlled by thermostats with scheduling and setpoint setback capabilities (CEC, 2015). In some cases, economizer controls, 2-speed supply fans, and DR functionality are also required.

INCUMBENT TECHNOLOGY

There isn't an existing technology that tries to do what the two evaluated emerging technologies do. However, since both technologies interfere with the signal that the thermostat is sending to the compressor, we could say that the incumbent technology is existing thermostat designs with all the flavors and capabilities that current thermostats have.

EMERGING TECHNOLOGY

Both controllers are intended to reduce energy consumption of packaged units by optimizing unit cycling operations. The controllers can be applied to most single zone heat pump and packaged air conditioning system such as those commonly found in small commercial buildings. This market is traditionally underserved by HVAC control technology offerings and presents a large opportunity for energy efficiency improvement. Additionally, the technology can also be applied at small refrigeration and residential package unit systems, but are not in the project scope.

Controller A is installed in series with an existing thermostat and interferes with compressor operations to maximize system efficiency. According to the manufacturer, the controller actively monitors and analyzes cycling operations to make decisions on how to optimally operate the compressor. Also, the controller operation can be remotely controlled. As shown in Figure 1 below, the decisions are made so that the compressor runs more often but for less time and in more efficient conditions by not running the compressor at lower suction temperature to achieve the lower end of the temperature dead band setting. The figure below is a visualization created by AESC and does not reflect exactly what the controller does since the algorithm is proprietary, but it helps explain the reasons for the expected energy savings.

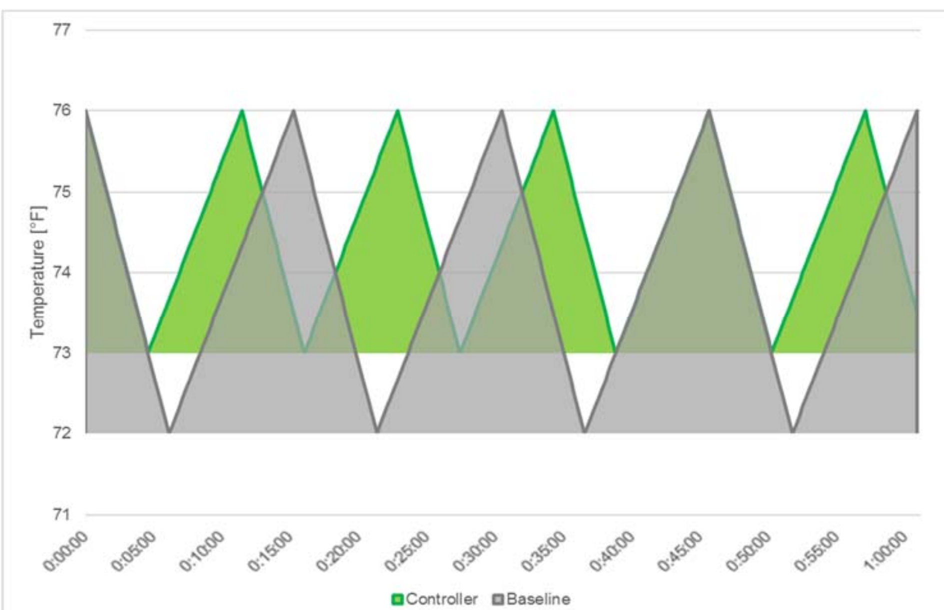


FIGURE 1: SIMPLIFIED EXAMPLE OF UNIT CYCLING OPERATION WITH AND WITHOUT CONTROLLER A

The installation is fairly simple and involves taking off the existing thermostat cover and mounting the controller to existing thermostat, which can take as little as 10 minutes. During phase 2, the manufacturer decided to use an older version of the same controller as the newer, remotely controllable version was found to have some issues. This required controllers to be mounted in the electric circuit board on the rooftop unit, which took approximately 30 minutes per unit to install.

Technology B also attempts to reduce the compressor run time and uses an additional temperature sensor in the return duct and evaporator to better monitor and control the space temperature. The controller is mounted on the electric circuit board on the rooftop unit by a certified HVAC technician. The installation takes typically 30 min to an hour per unit due to complexity involved in installation. The controller cannot be controlled remotely. This could be a negative feature for some customers, but preferred by other customers, such as military, because it is not susceptible to cyber-attack. Since the controller setpoint is manually set and fixed at the controller, installation can require additional commissioning to make sure that space comfort is met. In phase 1, the setpoint initially set during installation by the vendor was not changed for the duration of study. During phase 2, additional measurements were taken to ensure that the controller setpoint was in the expected range by monitoring the return air temperature.

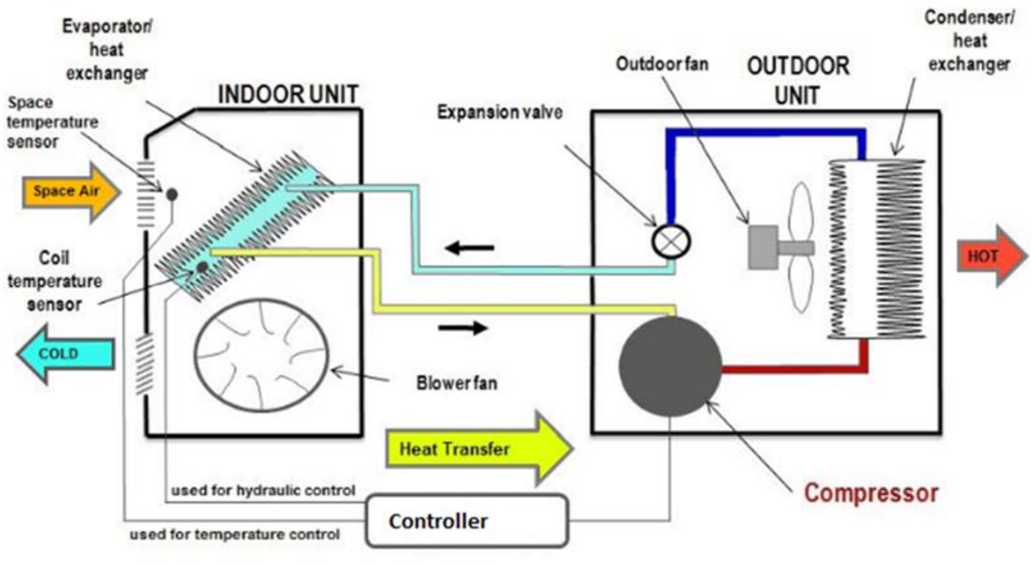


FIGURE 2: CONTROLLER B SCHEMATICS

MEASUREMENT AND VERIFICATION PLAN

A measurement and verification plan was established to capture all the necessary data to estimate energy savings of this technology. The plan followed the principles of the IPMVP standards and used Option B (Retrofit Isolation) M&V approaches. Retrofit isolation was exercised by monitoring the specific energy use of each packaged unit on an interval basis along with other variables to inform regression analyses. The following sections outline the specifics of the M&V plan including host site descriptions, instrumentation, and measurement timeline.

The controllers were evaluated at two office buildings with air-sourced heat pumps and air-cooled packaged units. The sites were vetted prior to M&V to assure that HVAC equipment was in proper working order and each unit was controlled with an appropriately scheduled thermostat.

Energy efficiency analysis was performed by monitoring the units on one-minute interval bases and using regressions to weather and business operations to project annual usage for the average weather year. The analysis included examination of hourly correlations to weather conditions, effect on overall compressor runtime and cycling frequency, and space temperatures.

HOST SITES

The host sites for the field trial were two office buildings in the SDG&E territory, one in El Cajon and one in Poway, CA. The building characteristics for both sites are listed in Table 1 below.

TABLE 1: HOST SITE BUILDING CHARACTERISTICS

CHARACTERISTIC	EL CAJON SITE	POWAY SITE
Building Type	Office	Office
Business Hours	8am – 5pm	8am- 5pm
Conditioned Floor Area [ft2]	6,500	8,500*
CA Climate Zone	10	10
Zip code	92020	92128

Both buildings are conditioned by packaged heat pumps with DX cooling. The packaged units were all less than 10 years old at the start of the study, well within the estimate EUL of 15 years. All units were controlled by programmable thermostat, which is accessible to the occupants. Table 2 lists the unit specifications.

TABLE 2: HOST SITE BUILDING CHARACTERISTICS

UNIT SPECIFICATIONS	EL CAJON SITE	POWAY SITE
Manufacturer	Bard	Carrier
Type	Wall-mounted packaged heat pump	Single-packaged rooftop heat pump
Heat rejection	Air	Air
Size [tons]	3 tons	2 to 6 tons
Thermostat	Programmable	Programmable

INSTRUMENTATION

PHASE 1

Data were collected using logging instrumentation from August 2016 to October 2016 at both office buildings. The logging lasted approximately six weeks for establishing a baseline and another six weeks for collecting data after the technology implementation.

The measurement points and the associated instrumentation are listed in Table 3 below. The variables in the table were continuously monitored and logged on an interval basis at AC circuit breakers and thermostat locations throughout the buildings. AC power data was captured on one-minute intervals to have high resolution data and understand any compressor or fan cycling that may have occurred. The outside air and indoor temperature data were collected on five-minute intervals.

TABLE 3: MONITORING INSTRUMENTATION

DATA POINT	MEASUREMENT	INSTRUMENT	ACCURACY	LOGGING INTERVAL
AC Power	Amps kW, kVA, A, V, pf	HOBO U12 PowerSight	±0.75% <1%	1 minute 1 minute
OAT and OARH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	5 minutes
INDT and INDRH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	5 minutes

PHASE 2

Data were collected from August 2017 to December 2017 using both wireless and traditional logging equipment at the office building in Poway. The controllers were switched on and off every two weeks to minimize the effect of uncontrolled variables. Three temperature sensors were added to each unit: One sensor was placed in the return duct to measure return air temperature (RAT), one in unit by the OA intake to measure mixed air temperature (MAT), and one in supply air duct to measure supply air temperature (SAT).

The measurement points and the associated instrumentation are listed in Table 4 below. The variables in the table were continuously monitored and logged at the AC circuit breakers and thermostat locations throughout the building. AC power data was captured on one-minute intervals to have high resolution data and understand any compressor or fan cycling that may have occurred. The outside air and indoor temperature data were collected on five-minute intervals and the RAT, MAT, and SAT were collected on ten-minute intervals, limited by the minimum interval allowed by the wireless sensor.

TABLE 4: MONITORING INSTRUMENTATION

DATA POINT	MEASUREMENT	INSTRUMENT	ACCURACY	LOGGING INTERVAL
AC Current	Amps	HOBO U12	±0.75%	1 minute
	Amps	Paranomic Power	<2%	1 minute
AC Power	kW, kVA, A, V, pf	PowerSight	<1%	1 minute
OAT and OARH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	5 minutes
INDT and INDRH	T/RH	HOBO U12	±0.63°F, ±2.5% RH	5 minutes
RAT	T	Monnit	±1.8°F	10 minutes
MAT	T	Monnit	±1.8°F	10 minutes
SAT	T	Monnit	±1.8°F	10 minutes

RESULTS – PHASE 1

The following analysis was made on each unit: verification of space temperatures in the conditioned space, regression of the power data to relevant independent variable (OAT), comparison of unit cycling operations on similar weather days. As mentioned in the executive summary, no savings were found for either technology at either site during phase 1 period.

CONTROLLER A

CONTROLLER A - EL CAJON SITE

The total of five units were monitored at the El Cajon site, but only four units were included in the analysis because the controller was not installed correctly for unit AC9. Figure 3 below shows the relationship between OAT and the energy demand of the packaged heat pump recorded during building occupied hours. The data in this chart was collected in one-minute interval. In both monitoring periods, the unit demand increased with the increasing outside air temperature as expected. Additionally, the unit demand corresponding to the same OAT is comparable before and after the retrofit, confirming that no change was made to the mechanical efficiency of the unit. The cloud of data below 1kW represents the fan energy when the unit was cycled off and only fan was running. The charts for the remaining units are included in the Appendices.

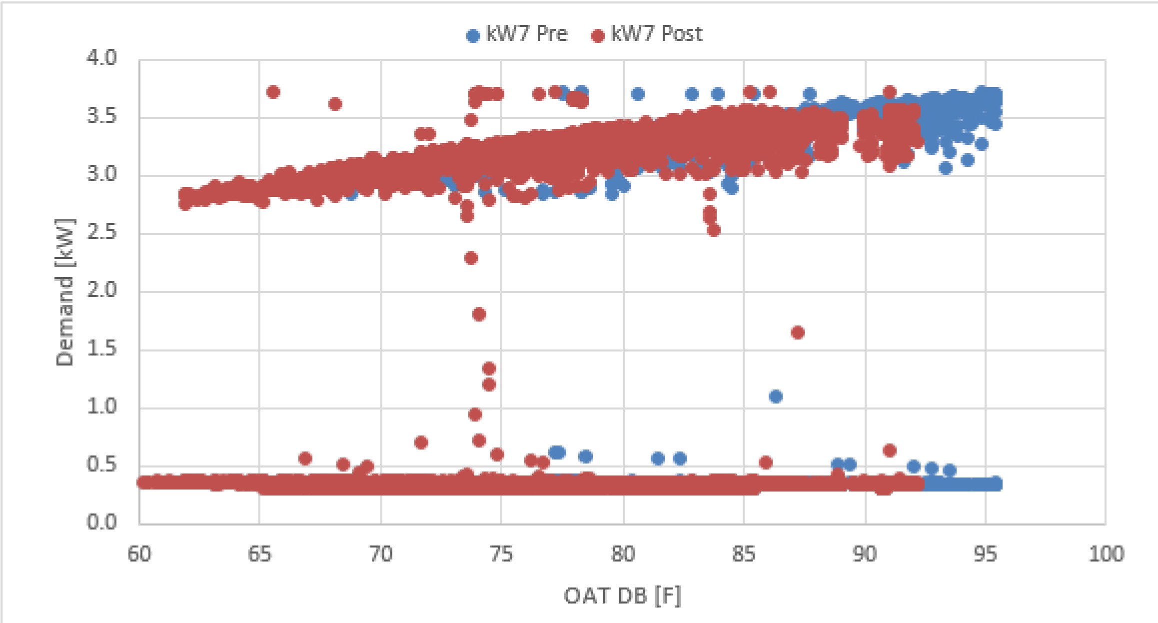


FIGURE 3: CONTROLLER A - EFFECT OF OUTSIDE AIR TEMPERATURE ON DEMAND DURING EACH MONITORING PERIODS

Two similar weather days were selected to compare the unit operation before and after the retrofit. For this unit (AC5), the unit cycled more frequently after the technology implementation. The unit cycled for 31 time during baseline and 57 times on a similar weather day after the retrofit. This is expected since the technology is supposed to increase the number of cycles while reducing the overall run time of the compressor. Similar behavior was observed for AC8. However, the number of cycles decreased for the other two units. Please refer to Appendices for details.

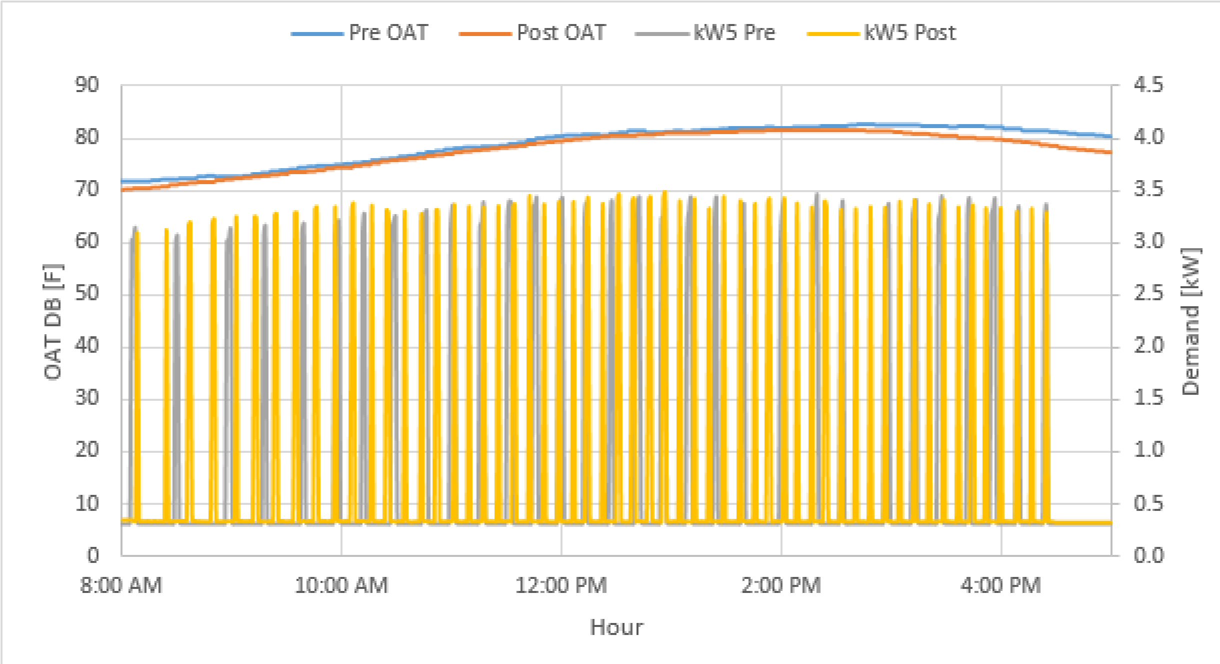


FIGURE 4: CONTROLLER A - UNIT CYCLING BEFORE AND AFTER THE INSTALLATION COMPARED DURING SIMILAR OUTDOOR TEMPERATURE DAYS

Average hourly indoor temperatures during operating hours show that indoor conditions were kept relatively consistent over the course of study for all units. This information is important to verify that savings, if any, are not achieved at the expense of occupant comfort and indoor air quality. The average indoor air temperatures during operating hours for one of the packaged units are plotted in Figure 5 below.

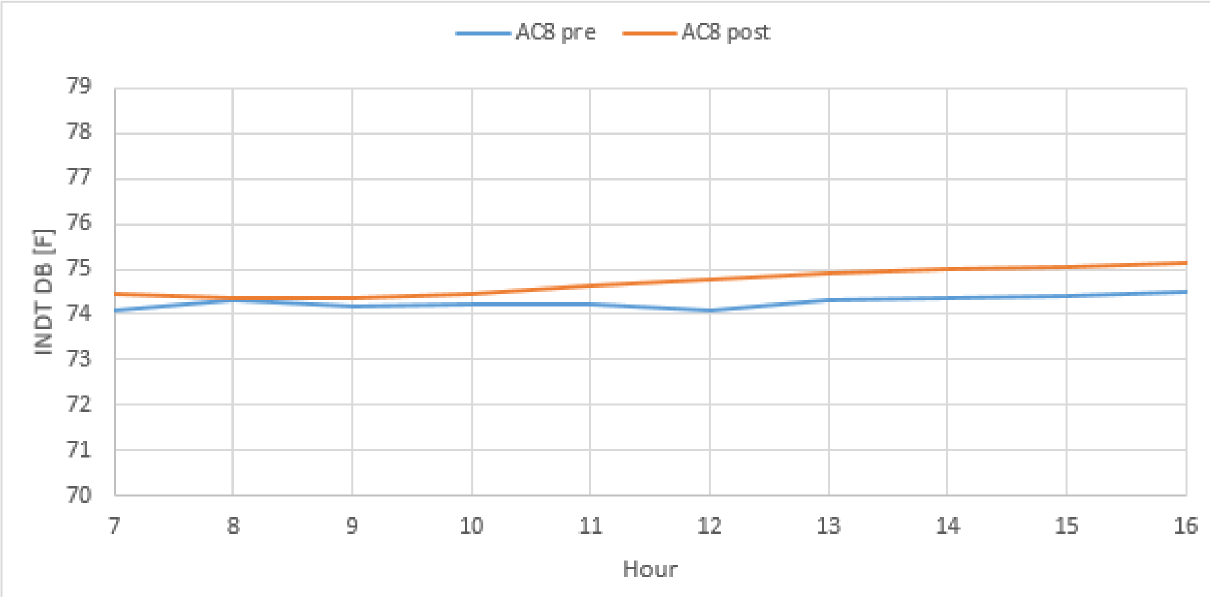
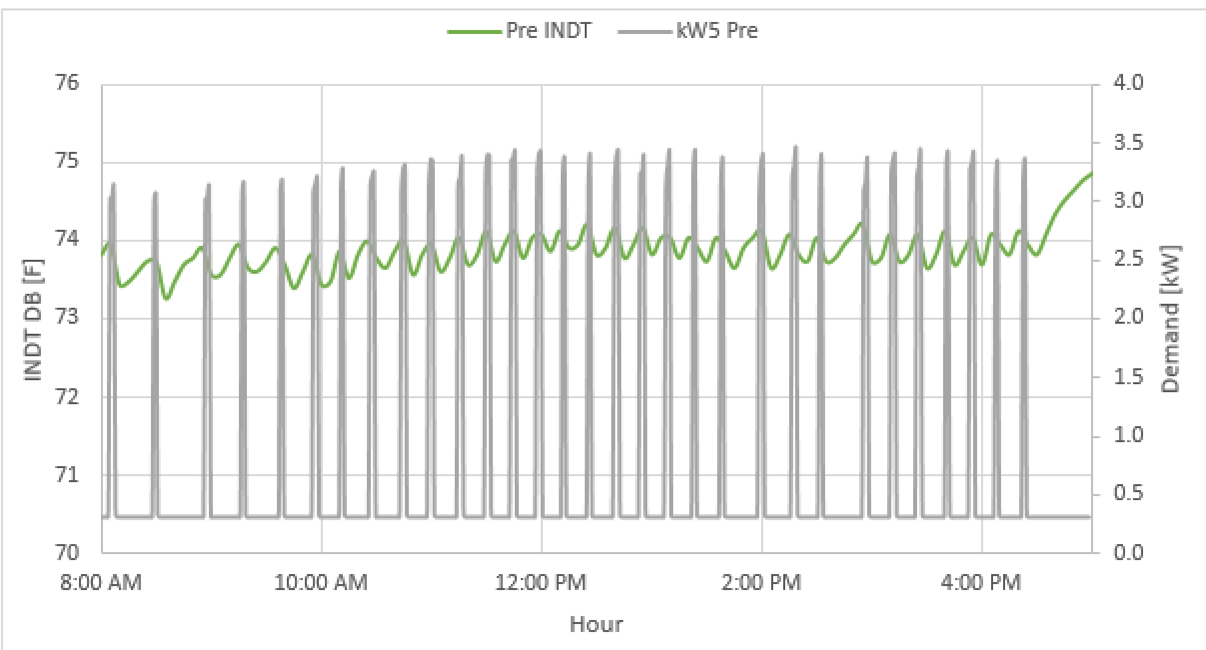


FIGURE 5: CONTROLLER A - AVERAGE INDOOR TEMPERATURES FOR EACH MONITORING PERIOD DURING OCCUPIED HOURS

The compressor cycling and minute by minute change in space temperature on two similar weather days were plotted on the same chart in Figure 6. The charts clearly show the difference in control strategy between the traditional thermostat and the installed controller.



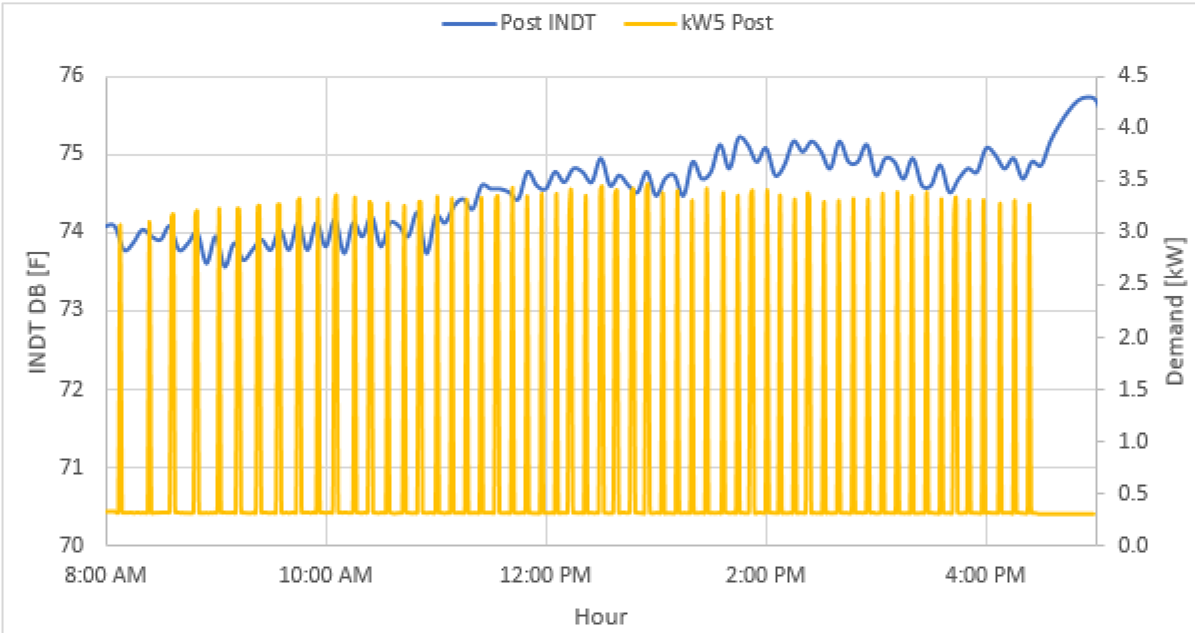


FIGURE 6: CONTROLLER A COMPRESSOR CYCLING AND INDOOR AIR TEMPERATURE ON TWO SIMILAR DAYS PRE AND POST INSTALLATION

Regressions of total hourly average demands to hourly average outside temperature were established to estimate annual consumptions and shown in Figure 7. At this site, the total hourly average demands of all packaged units were slightly greater after the technology installation, both at each unit level and across the five units combined. The result indicates that the implemented technology allowed the compressors to run longer on average after the retrofit. The regression analysis suggests an annual increase in energy consumption.

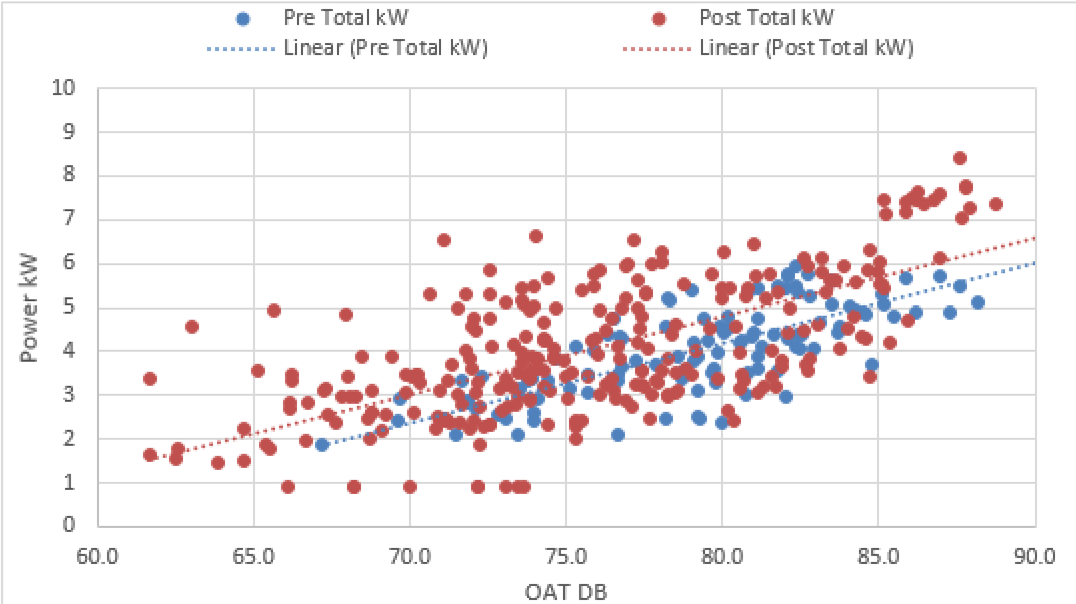


FIGURE 7: CONTROLLER A AT EL CAJON SITE HOURLY SCATTER PLOTS OF UNIT DEMAND AS A FUNCTION OF OAT PRE AND POST INSTALLATION

CONTROLLER A - POWAY SITE

Five RTUs were also monitored at the Poway site. Figure 8 below shows the relationship between OAT and the energy demand of the packaged heat pump recorded during building occupied hours. The data in this chart were collected in one-minute intervals. In both pre- and post-installation monitoring periods, the RTU demand increased with the increasing outside air temperature, which is typical for vapor compression cycle units. The cloud of data just below 1kW represents the fan energy when the RTU compressor was cycled off and only the supply fan was running. The charts for the remaining RTUs are included in the Appendices.

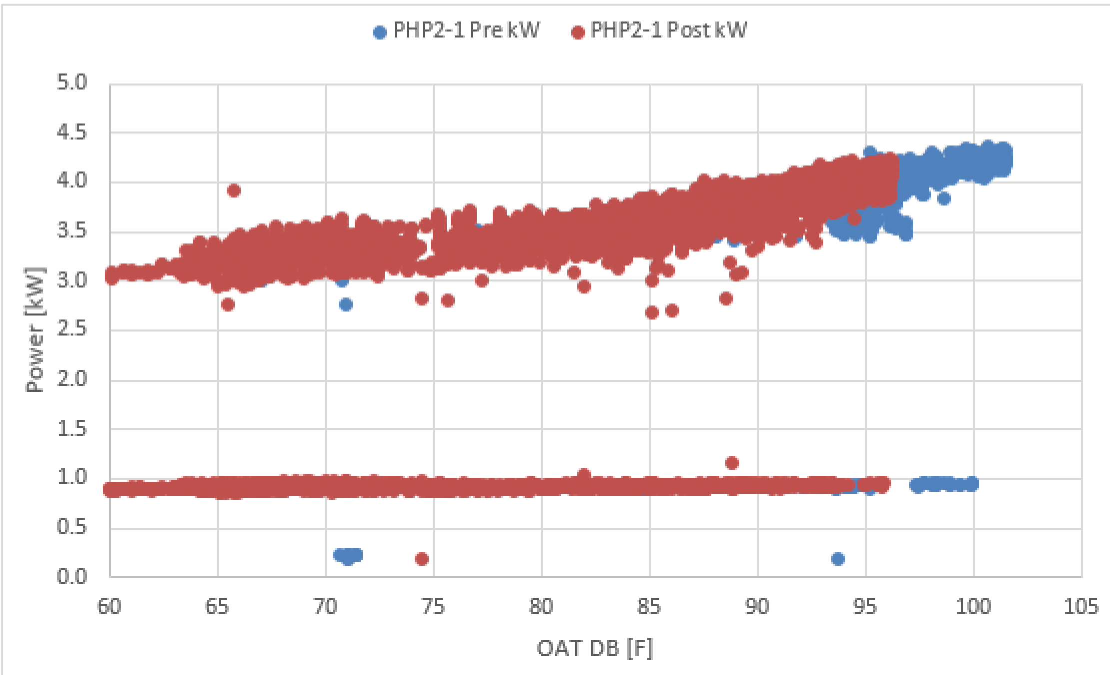
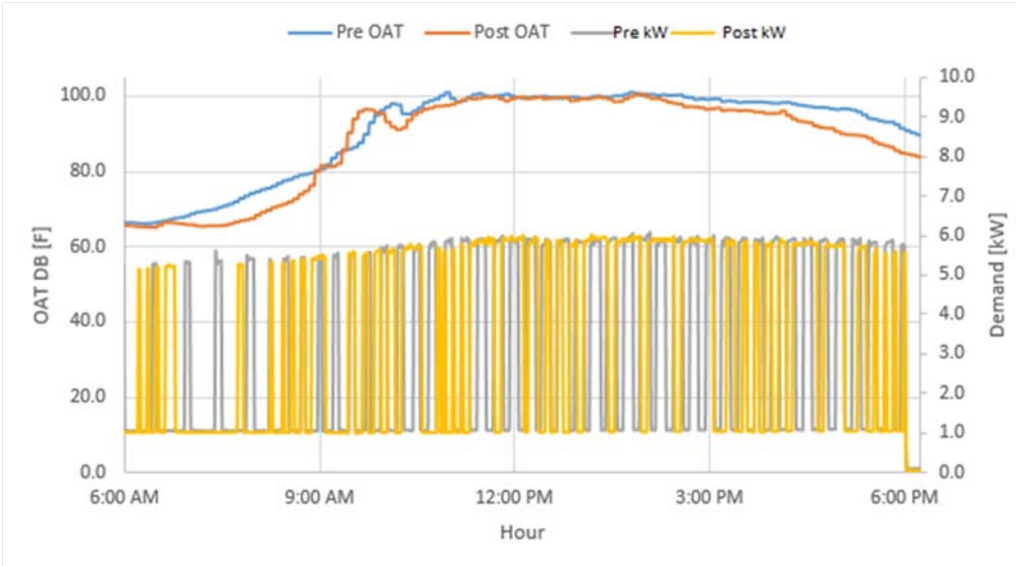


FIGURE 8: CONTROLLER A - EFFECT OF OUTSIDE AIR TEMPERATURE ON DEMAND DURING EACH MONITORING PERIOD

The cycling operations of the RTU PHP2-7 on two similar weather days were compared in Figure 9 below. The number of cycles was similar on both days (approximately 40 cycles per day), but there is a difference in the way the compressor was run. While the traditional thermostat's control band was less than 1°F, the controller A allowed the space temperature to drift ± 1.5°F from the setpoint. The data also shows that setpoint temperature was changed. On the day that was chosen during the baseline period, the space temperature was kept at around 75.5°F while the space temperature averaged around 74°F on the day chosen during the retrofit period. Since the thermostat was accessible to the occupants, it is likely that the occupants changed the thermostat setpoint during the study. Please refer to Appendices for the charts for other RTUs.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Post OAT
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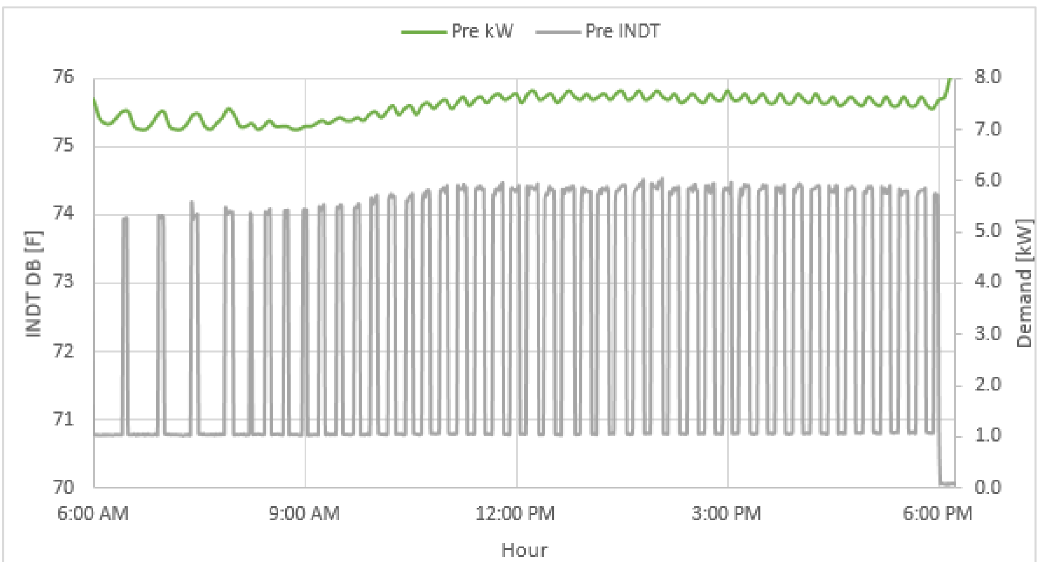
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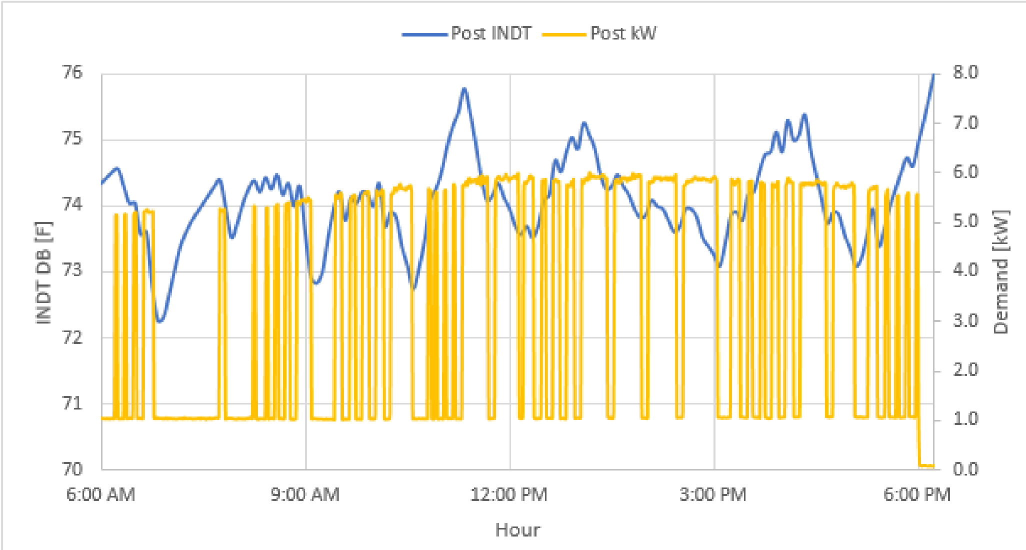


FIGURE 9: CONTROLLER A- COMPRESSOR CYCLING AND INDOOR AIR TEMPERATURE ON TWO SIMILAR DAYS PRE AND POST INSTALLATION

Regression analysis was performed for each RTU individually and for the site as a whole. As shown in Figure 10, no notable change was observed in the average hourly demand for each RTU before and after the technology implementation. Note PHP2-9 was excluded from the analysis because space temperature setpoint appeared to have changed more than 2°F between the two monitoring periods. Please refer to Appendix I for the unit by unit analysis.

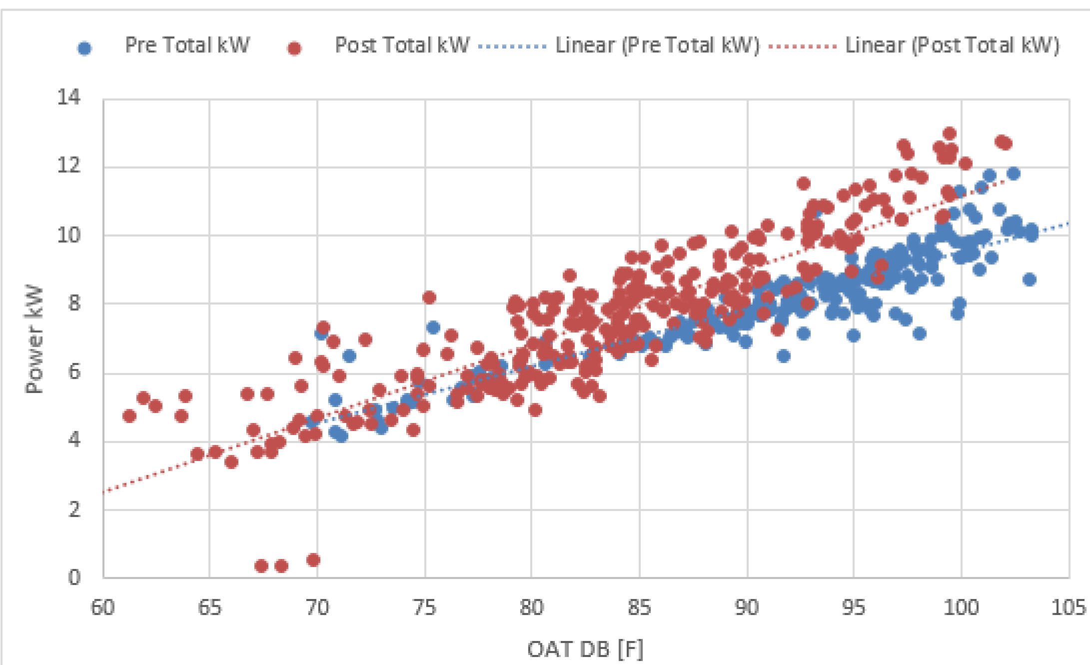


FIGURE 10: CONTROLLER A POWEY SITE HOURLY SCATTER PLOTS OF RTU DEMAND AS FUNCTION OF OAT PRE AND POST INSTALLATION

CONTROLLER B RESULTS

CONTROLLER B - EL CAJON SITE

The total of five units were studied at El Cajon site for controller B. Figure 11 below shows the effect of OAT on the energy demand of a packaged unit during building occupied hours. The data were collected in one-minute intervals. The unit demand increased with the increasing outside air temperature as expected in both monitoring periods. The cloud of data below 0.5 kW represents the fan demand when the compressor was cycled off and only the supply fan was running. All units showed similar behavior and plots for the remaining units are included in the Appendices.

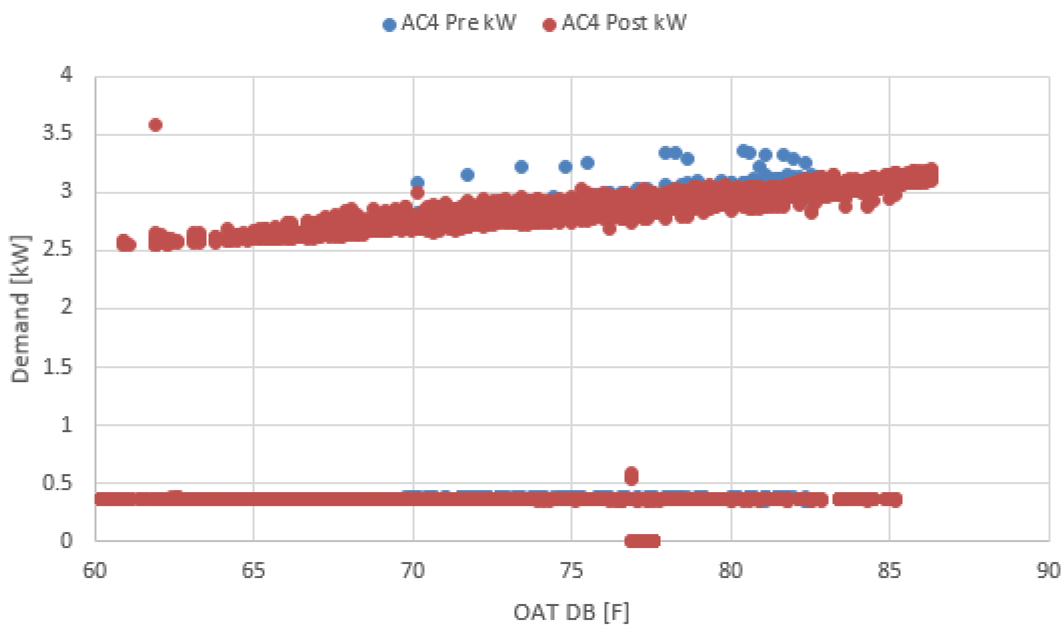


FIGURE 11: CONTROLLER B - EFFECT OF OUTSIDE AIR TEMPERATURE ON UNIT DEMAND DURING EACH MONITORING PERIODS

The unit operation before and after technology instrumentation were compared on similar weather days in Figure 12 below to study the cycling behavior. The figure illustrates that cycling behavior was similar before and after the retrofit (12 cycles per day before and 13 cycles per day after). The duration of compressor "on" time was also similar. The result is similar for all the units and the charts for remaining units can be referenced in Appendices.

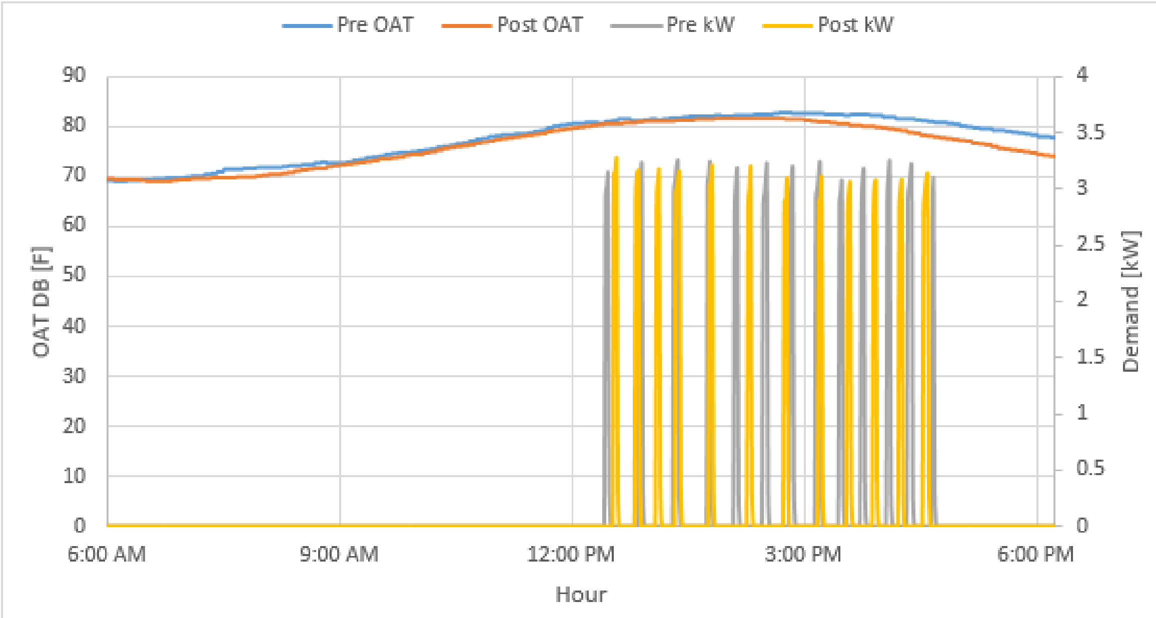


FIGURE 12: CONTROLLER B - UNIT CYCLING BEFORE AND AFTER THE INSTALLATION COMPARED DURING SIMILAR OUTDOOR TEMPERATURE DAYS

Figure 13 below shows the similar weather day comparison of another unit. On this particular unit (AC4), the unit cycled similarly before noon, but showed different operation pattern in the afternoon. Although OAT was slightly lower in the post, the unit operated continuously in the afternoon while it cycled several times during the baseline period. A few possibilities were considered for this change in operation. First, this could be the optimum operation of the unit as intended by the controller B. That is not likely however, as the most optimum operation of the controller would be to cycle on for the duration of 4-7 minutes per cycle according to the manufacturer. Second, the controller's return air temperature setpoint for this space could be set too low. However, the space temperature data shows that this was not the case. Finally, there could have been an increase in space cooling load such as increased occupancy or activity level in the space during the post period. Since the occupancy or activity level of the space was not monitored as part of the study, the increase in load couldn't be confirmed.

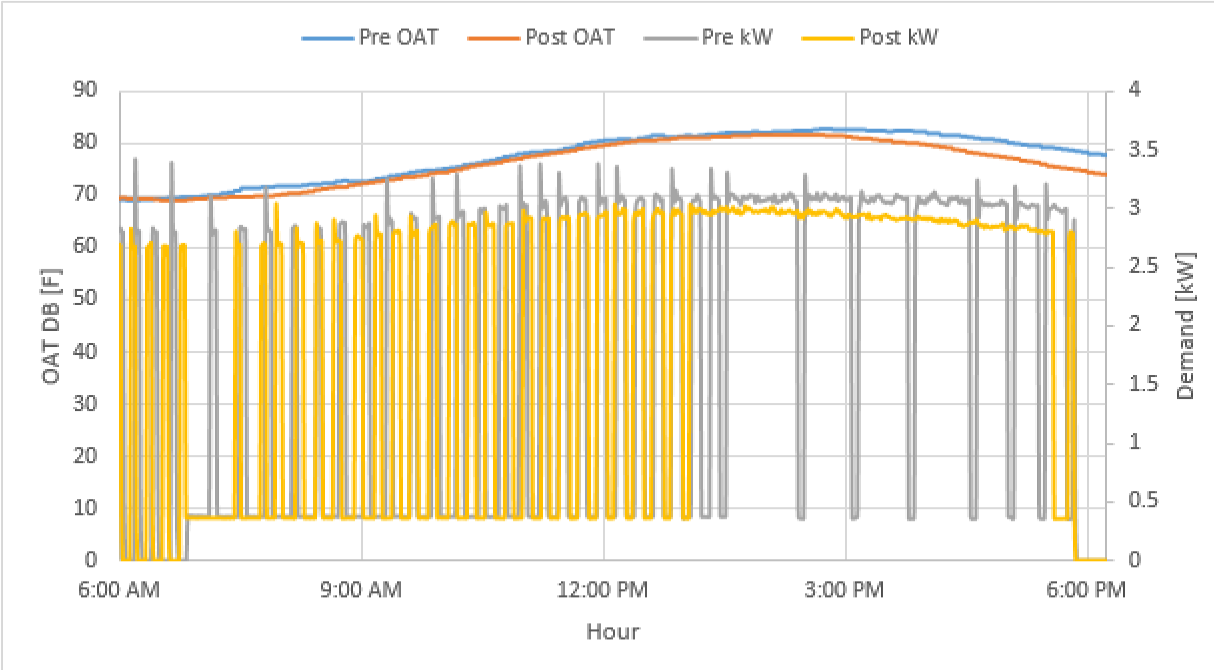


FIGURE 13: CONTROLLER B - COMPARISON BEFORE AND AFTER INSTALLATION FOR UNIT

Finally, regression analysis was performed to evaluate the hourly average demands of the site to hourly average outside temperature. The analysis concluded that no savings were observed at the unit level nor as an aggregate of all five units. Figure 14 below represents the regression analysis performed for all five units combined. The analysis shows that the average hourly demands of the packaged units were slightly higher during the post retrofit period in all temperature ranges, indicating that the compressors ran longer on average after the technology installation.

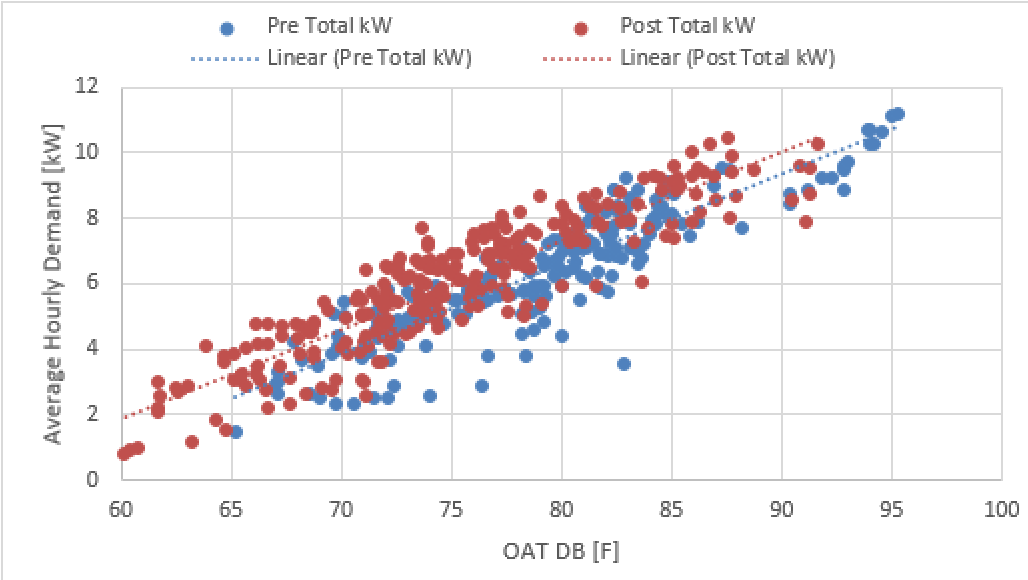


FIGURE 14: CONTROLLER B EL CAJON SITE HOURLY SCATTER PLOTS OF UNIT DEMAND AS FUNCTION OF OAT PRE AND POST INSTALLATION

Controller B - Poway Site

A total of five units were also studied at the Poway site. The effect of OAT on the energy demand of the RTUs at the site during building occupied hours was plotted in Figure 15. Although small, the RTU demand increased with the increasing outside air temperature in both monitoring periods as expected for vapor compression cycle units. The cloud of data below 0.5 kW represents the fan demand when the compressor was cycled off and only the supply fan was running. All RTUs showed similar behavior and plots for the remaining RTUs are included in the Appendices.

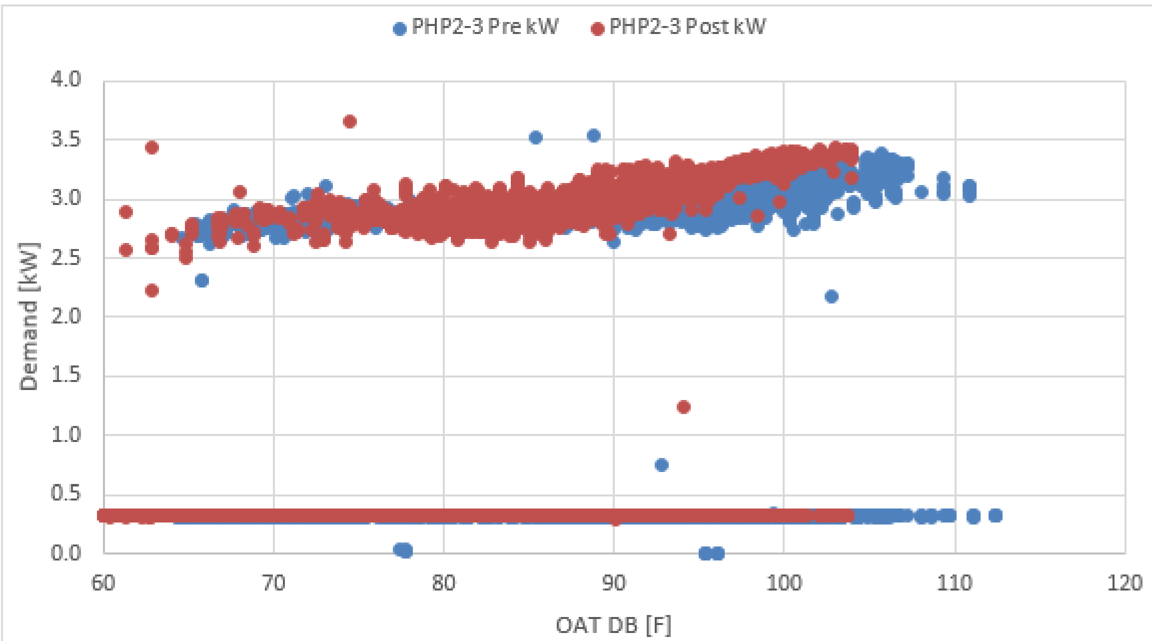
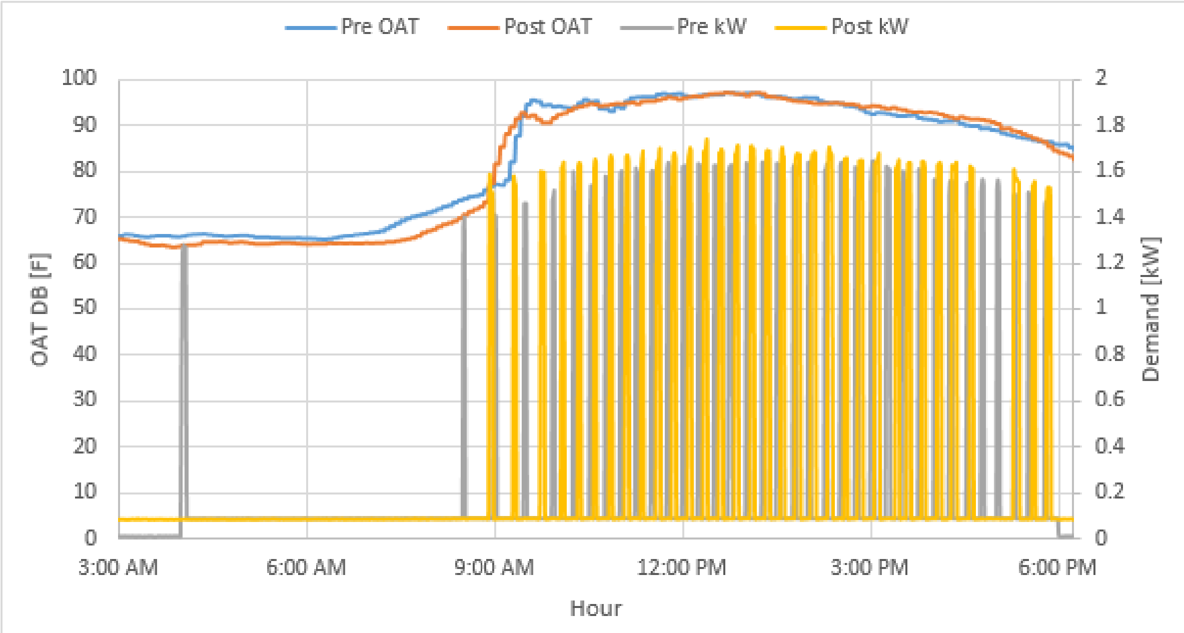
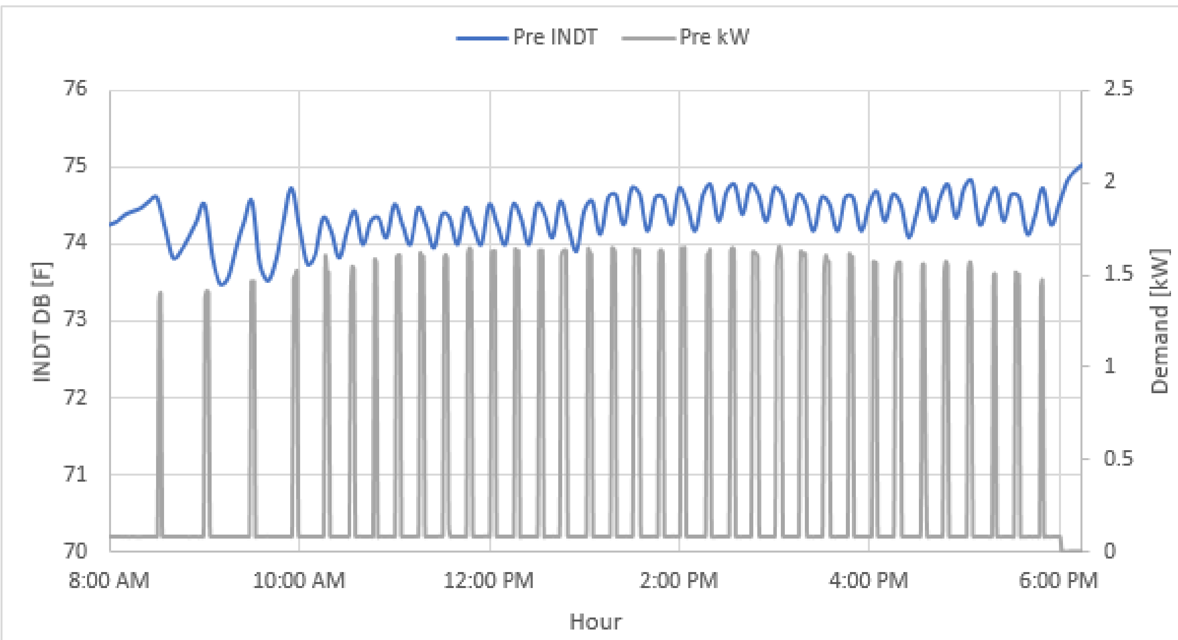


Figure 15: Controller B - minute average demand befor and after installation

Figure 16 compares the RTU's operation before and after technology installation. Two similar weather days were selected so that the loading on the RTU would be comparable. The plot shows the RTU cycled 36 times before and 33 times after the retrofit. The duration of time when compressor was "on" was slightly shorter in the post period with the average of six minutes per cycle during the baseline and four minutes per cycle during the post period. The result is typical for all RTUs and the charts for the remaining RTUs can be referenced in Appendix II.


Pre OAT
Post OAT
Pre kW
Post kW
100
90
80
70
60
50
40
30
20
10
0
OAT DB [F]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Demand [kW]
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour


Pre INDT
Pre kW
76
75
74
73
72
71
70
INDT DB [F]
2.5
2
1.5
1
0.5
0
Demand [kW]
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM
6:00 PM
Hour

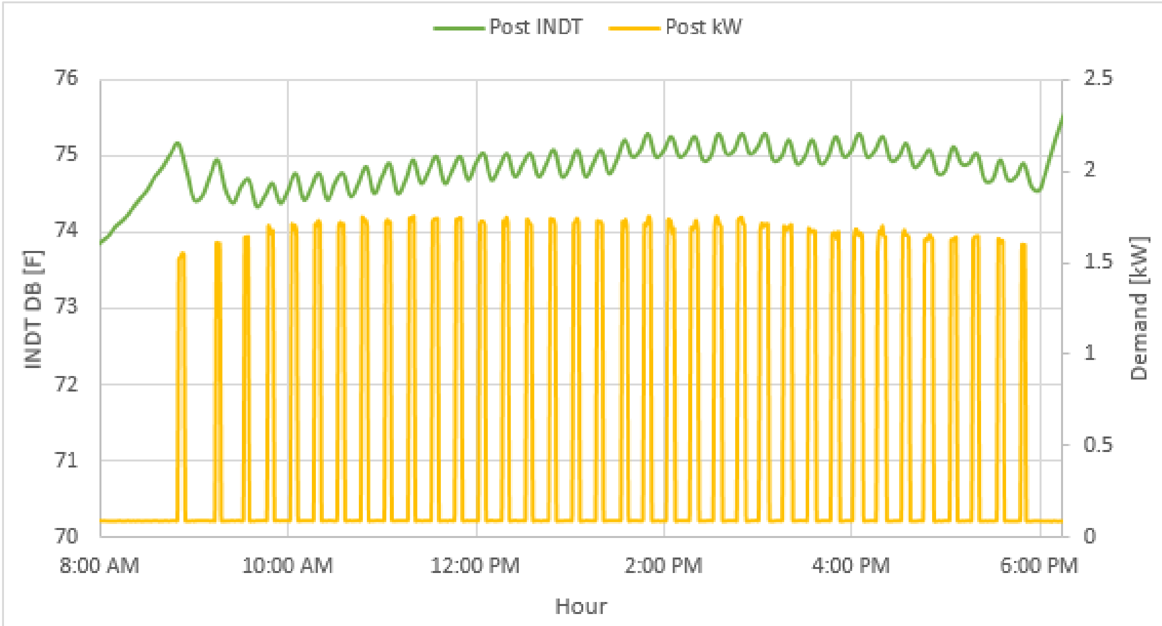


FIGURE 16: CONTROLLER B - COMPRESSOR CYCLING AND INDOOR AIR TEMPERATURE ON TWO SIMILAR DAYS PRE AND POST INSTALLATION

Regression analysis was performed to evaluate the hourly average demand of each RTU at the site to hourly average outside temperature. The analysis concluded that no significant savings were observed except for RTU PHP2-10, which is shown in Figure 17 below. However, the temperature profile of space served by the PHP2-10 showed that the RTU was not able to maintain the setpoint, allowing the temperature to increase above 78°F. It is possible that the baseline thermostat temperature was affected by direct radiation from the sun during the baseline, resulting in additional calls for cooling. Due to the additional return temperature sensor installed with Controller B, the retrofit would not have that same issue. Therefore, further investigation and testing would be needed to verify the savings seen on PHP2-10. For this reason, the result of this RTU was not included in the totals results for the site.

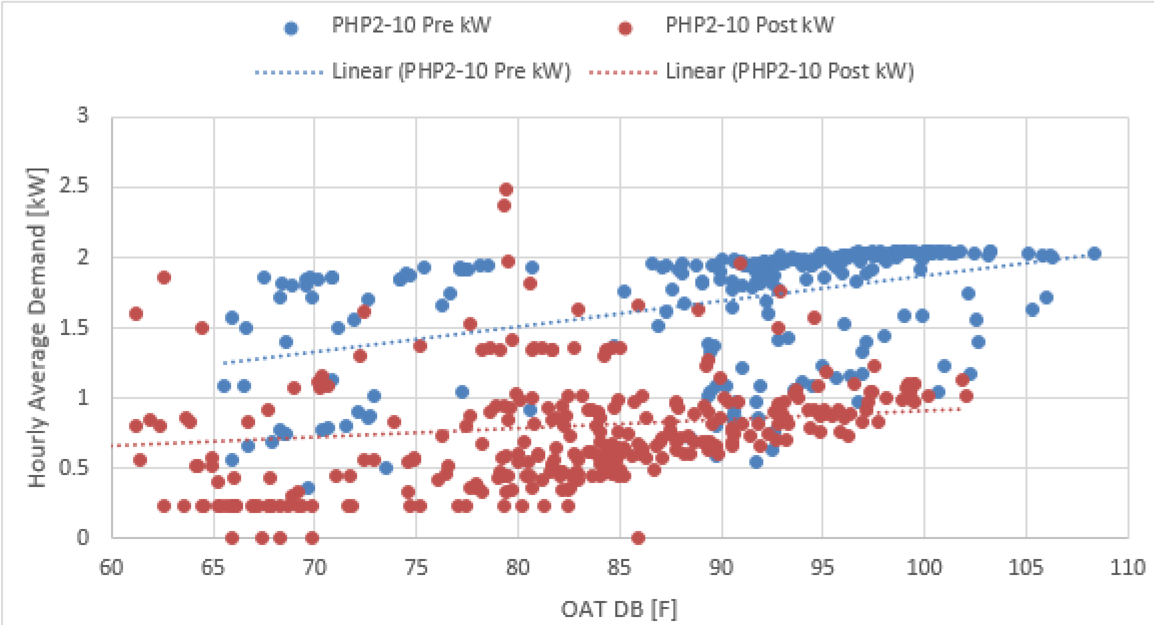


FIGURE 17: CONTROLLER B - SCATTER PLOT OF RTU PHP2-10 HOULY DEMAND AS FUNCTION OF OAT PRE AND POST INSTALLATION

Figure 18 below represents the regression analysis performed for the four RTUs combined, excluding PHP2-10. The analysis shows that the average hourly demands of the RTUs were slightly higher during the post retrofit period in all temperature ranges, indicating that the compressors ran longer on average after the technology instrumentation.

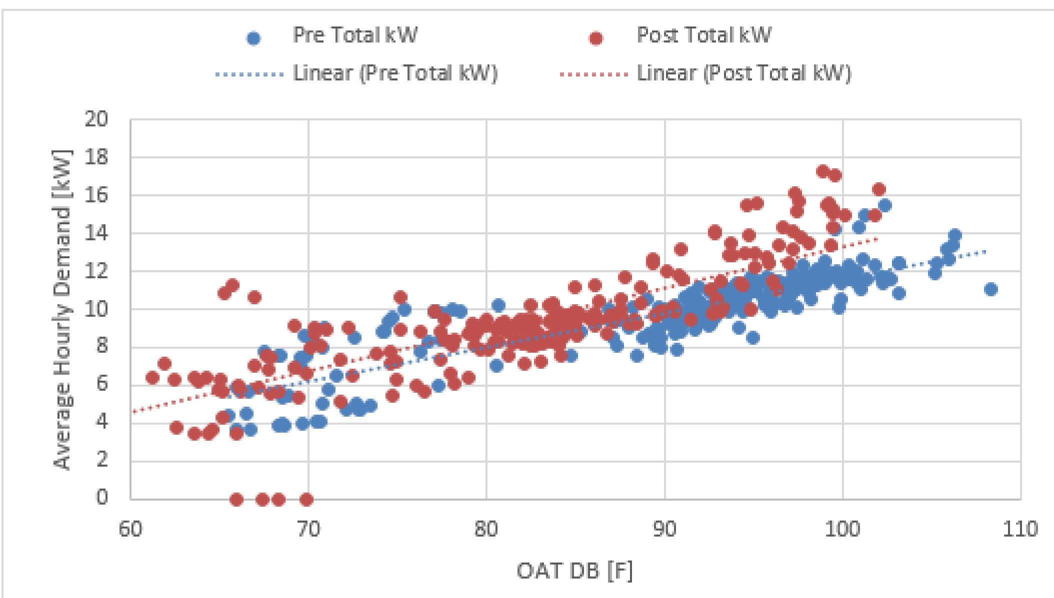


FIGURE 18: CONTROLLER B POWEY SITE HOURLY SCATTER PLOTS OF RTU DEMAND AS FUNCTION OF OAT PRE AND POST INSTALLATION

RESULTS – PHASE 2

As follow up to the phase 1 results, phase 2 M&V was performed from August 2017 to December 2017 at the Poway site. During this phase, three temperature sensors were added to each unit so that cooling load can be calculated to minimize the uncertainty related to the change in cooling load resulting from thermostat setpoint and occupant activity level changes. One sensor was placed in the return duct to measure return air temperature (RAT), another was placed in unit to measure mixed air temperature (MAT), and the third was placed in supply air duct to measure supply air temperature (SAT). Additionally, the controllers were switched on and off every two weeks to minimize seasonal and occupant variability that may have been present during phase 1.

Using the supply and mixed air temperature data and the nameplate nominal airflow (CFM), the cooling load (Q) of each unit was calculated as following:

$$Q = 1.1 \cdot CFM \cdot (MAT - SAT)$$

$$Q = unit\ cooling\ load\ [ton]$$
$$MAT = mixed\ air\ temperature\ [°\mathrm{F}]$$
$$SAT = supply\ air\ temperature\ [°\mathrm{F}]$$

The regression analysis was performed on each unit with hourly average power as dependent variable and cooling load as independent variable. With the calculated cooling load, the R^2 value improved greatly over phase 1 results. Most analysis achieved R^2 value of 0.9 or greater. Additionally, small savings were observed for two units with controller A and for all units with Controller B.

CONTROLLER A

Three more units were added to the study because one of five units tested during phase 1 was found to be undersized. Since the controller saves energy by cycling the compressor more frequently, the technology is not fit for units that are undersized and do not cycle often. Thus, a total of eight units were studied at the Poway site during Phase 2. Regression analysis was performed to evaluate the hourly average demand of RTU to hourly average cooling load for each unit as well as the sum of all units. The analysis concluded that no significant savings were observed when all eight units were combined (Figure 19). In below charts, “Controller OFF” indicates time when the controllers are disabled or pre-retrofit condition and “Controller ON” indicates that the technology was enabled or post-retrofit condition.

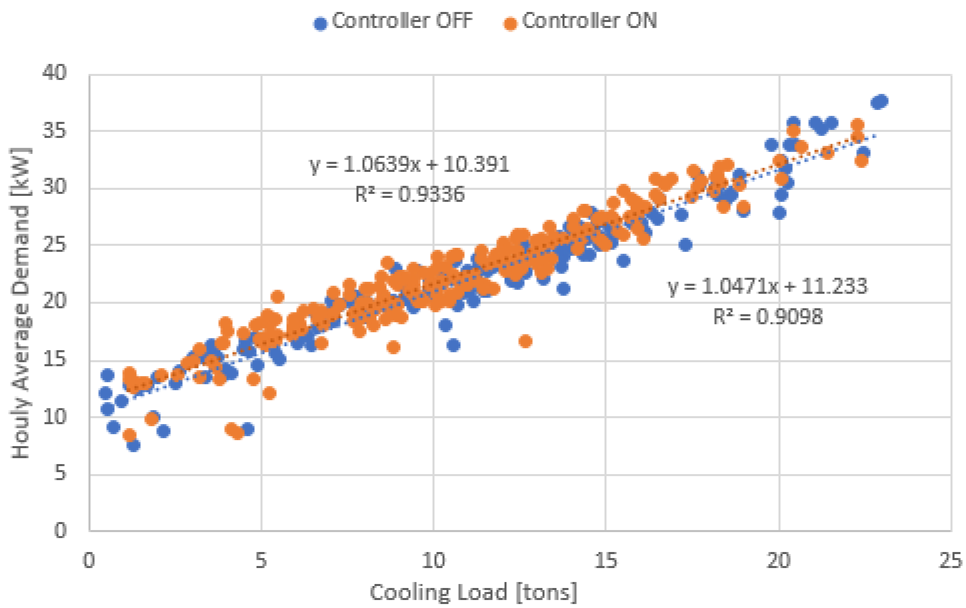


FIGURE 19: SCATTER PLOT OF HOURLY RTU DEMANDS AS FUNCTION OF COOLING LOAD FOR ALL UNITS COMBINED

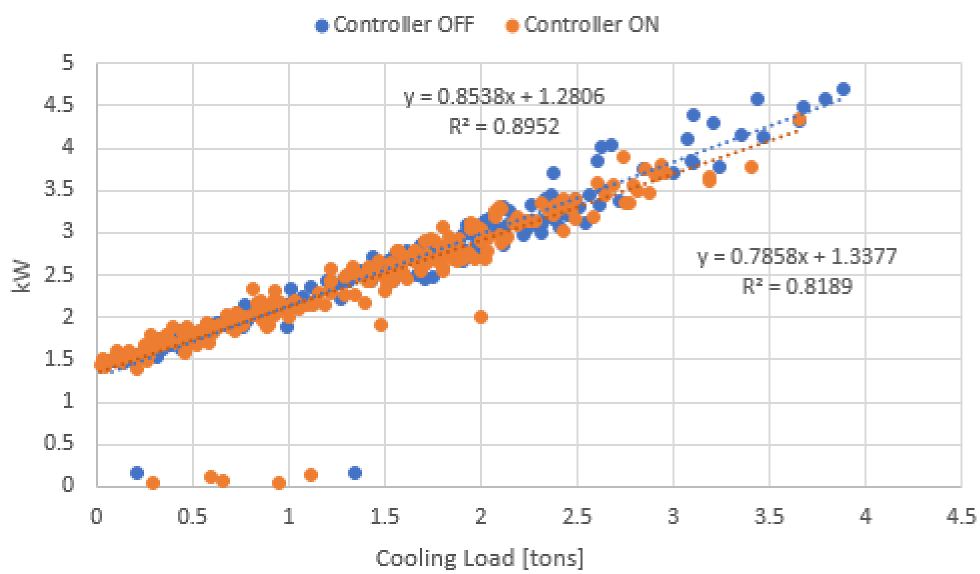


FIGURE 20: SCATTER PLOT OF HOURLY RTU DEMANDS AS FUNCTION OF COOLING LOAD FOR PHP-12

CONTROLLER B

A total of five units, unchanged from phase 1, was studied at the Poway site. During phase 2, the controller's return air temperature sensor was elongated approximately two to three feet so that it could be placed well into the return duct to minimize the effect of ambient temperature and solar radiation, which was suspected during phase 1. The controller setpoint was also commissioned using return air temperature data recorded by the wireless temperature sensor, also placed in the return duct two feet below the unit. The location of the sensor is important because the controller uses the return air temperature to determine the timing of unit cycling. The collected data was used to perform regression analysis to evaluate the hourly average demand of RTU to hourly average cooling load for each unit as well as all units combined. The analysis concluded that small savings were observed for all units.

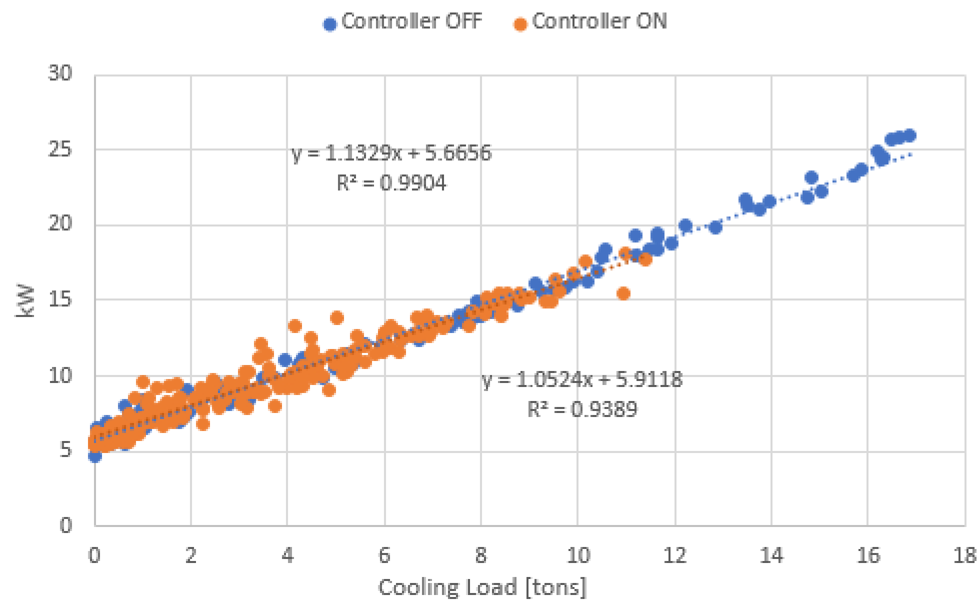


FIGURE 21: SCATTER PLOTS OF HOURLY RTU DEMANDS AS FUNCTION OF COOLING LOAD FOR ALL UNITS COMBINED

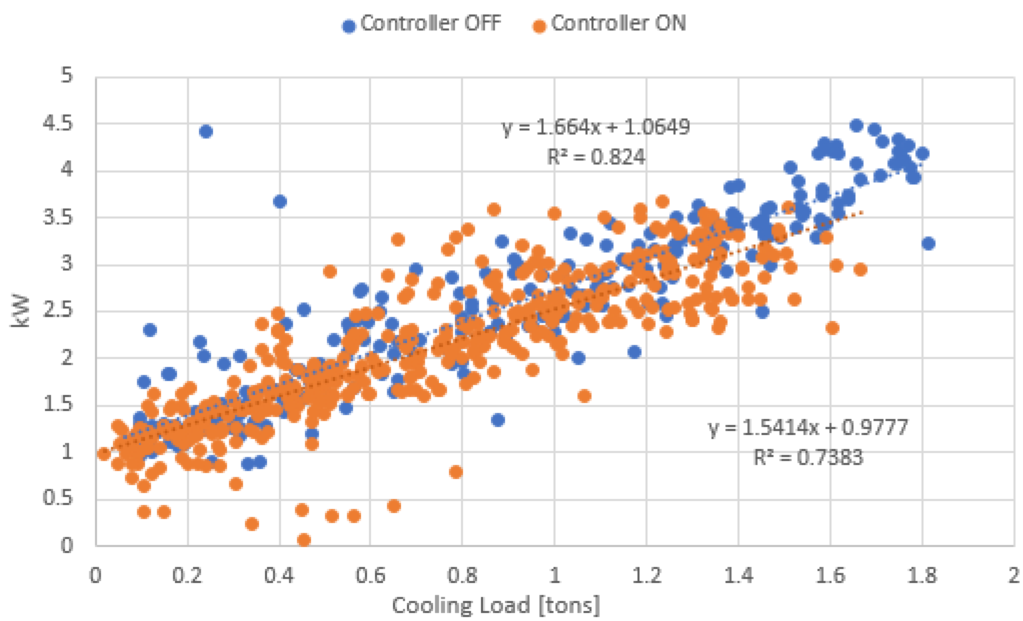


FIGURE 22: SCATTER PLOTS OF HOURLY RTU DEMANDS AS FUNCTION OF COOLING LOAD FOR PHP-3, SHOWING SMALL SAVINGS

Controller B Annual Normalized Savings

Since small savings were observed for all units with controller B, expected annual savings were calculated using CZ2010 weather data. The table below represents the savings calculated for all five units combined, which amounts to 19 nominal tons total. As described in previous sections, the regression was made to correlate cooling load and the power demand, but not to ambient conditions. Therefore, additional regression was created to correlate the outside dry-bulb air temperature and cooling load (Figure 23). The regression resulted in R^2 value of 0.83. Using the regression model, cooling load and total demand were calculated hourly from 7am to 6pm during the weekday only, although the units at the Poway site operated on some Saturday mornings. The results showed maximum of 2% savings for climate zones 14 and 15. The resulting savings are insignificant given that the percent savings didn't exceed the margin of error of the monitoring instrumentations used.

Table 3 – Annualized Phase 2 Savings for Controller B (5 Combined RTUs)

Climate Zone	kWh Saved	Percent
7	0	0%
10	380	1%
14	610	2%
15	1,160	2%

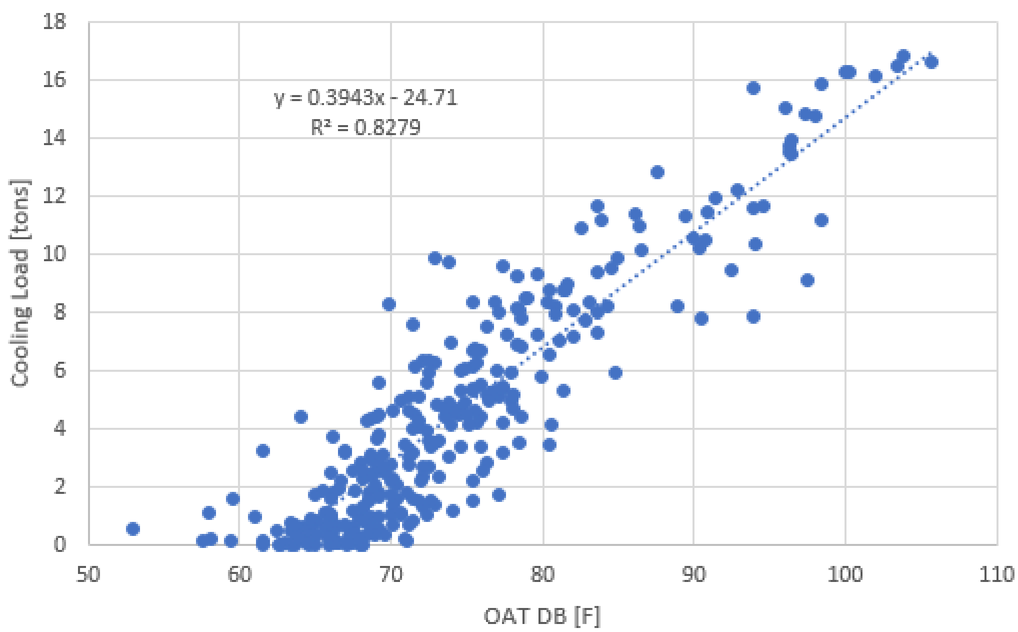


Figure 23 – Scatter plots of cooling load as function of outside air temperature

CONCLUSION

The phase 1 analysis of data showed that neither of the two controllers saved energy at the selected sites. It was speculated that uncontrolled factors such as thermostat setting, occupancy rate, and occupancy activity level, as well as seasonal change in solar radiation affected the units' operations. Moreover, a couple of units operated at full load condition for extended periods of time. Since the controller saves energy by modifying the cycling behavior, these units would not have benefitted from the addition of the technology.

To resolve the issues observed during phase 1, phase 2 test was performed from August 2017 to December 2017. The following modifications were made to eliminate as much uncertainty as possible.

- The length of study was increased from 12 weeks to 18 weeks.
- The controllers were turned on/off every two weeks.
- Three units with controller A were added to study.
- To mitigate the load change due to thermostat setpoint change, mixed air temperature and supply air temperature sensors were added so that cooling load can be calculated.
- Controller B's return air temperature sensor was extended to mitigate confounding influences.
- Return air temperature sensors were added so that controller B's setpoint could be commissioned.

The phase 2 results improved statistical significance, but showed insignificant savings with the maximum calculated annual savings of two percent for controller B. Although each controller only cost a few hundred dollars each, the total cost becomes much higher because they need to be installed by a certified HVAC technician. Thus, the calculated savings are not great enough to achieve desired simple payback as is. With assumed blended rate of $0.20 per kWh and controller cost of $500 per unit (not including commissioning cost), the simple payback was calculated to be over 10 years.

Given that the control strategy makes sense and that controllers have shown savings in other applications (i.e. refrigeration) or in other climate zones/countries, we believe that the technology may have potential to save energy in right applications. For the controllers to be adopted in commercial buildings in SDG&E territory, however, the following issues need be addressed before they can be considered for packaged RTUs applications:

- The controllers will only work (save energy) on units with certain conditions. Currently there is no screening criteria to ensure that the units are suitable for the technology:
    - Since savings are dependent on unit cycling, the unit must not be undersized.
    - The unit should operate in part load, ideally in 40% to 60% load range.
    - The units must be properly maintained in good condition for the technology to work.
- It requires HVAC technician to install the controllers and installation is difficult if the technician is not trained, especially for dual compressor units.
- The controllers require commissioning once installed:
    - By design, controller B overrides the thermostat temperature setpoint. Therefore, the controller B's setpoint, set manually at the controller installed inside of RTU, must be commissioned to ensure the desired indoor temperature is achieved. This process should be automated or the controller panel should be more accessible to the user.
    - Controller A may also be installed inside of RTU, which is not easily accessible.

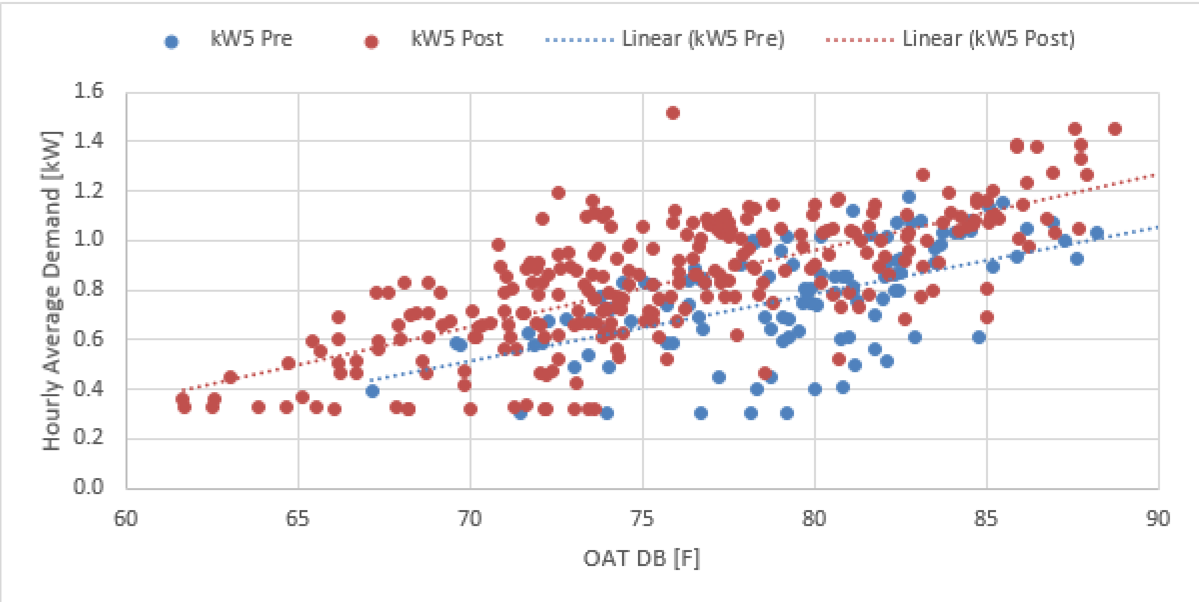
- The locations of return air and evaporator temperature sensors are critical for controller B and therefore should be commissioned or installation instruction should be made clearer.

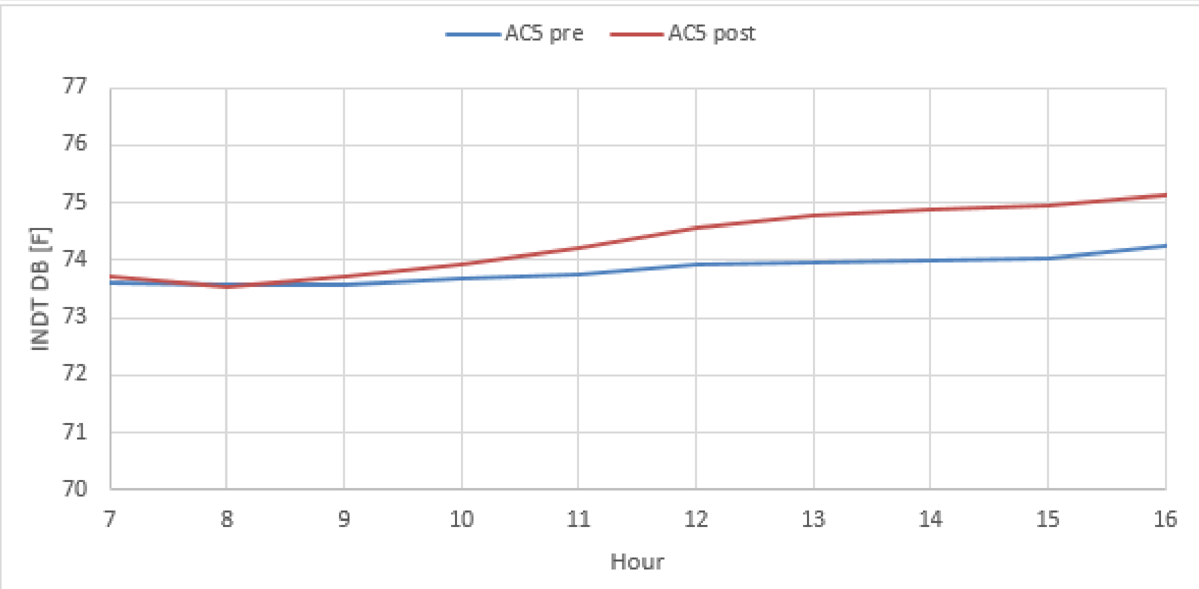
APPENDIX I – PHASE 1 CONTROLLER A UNIT BY UNIT ANALYSIS

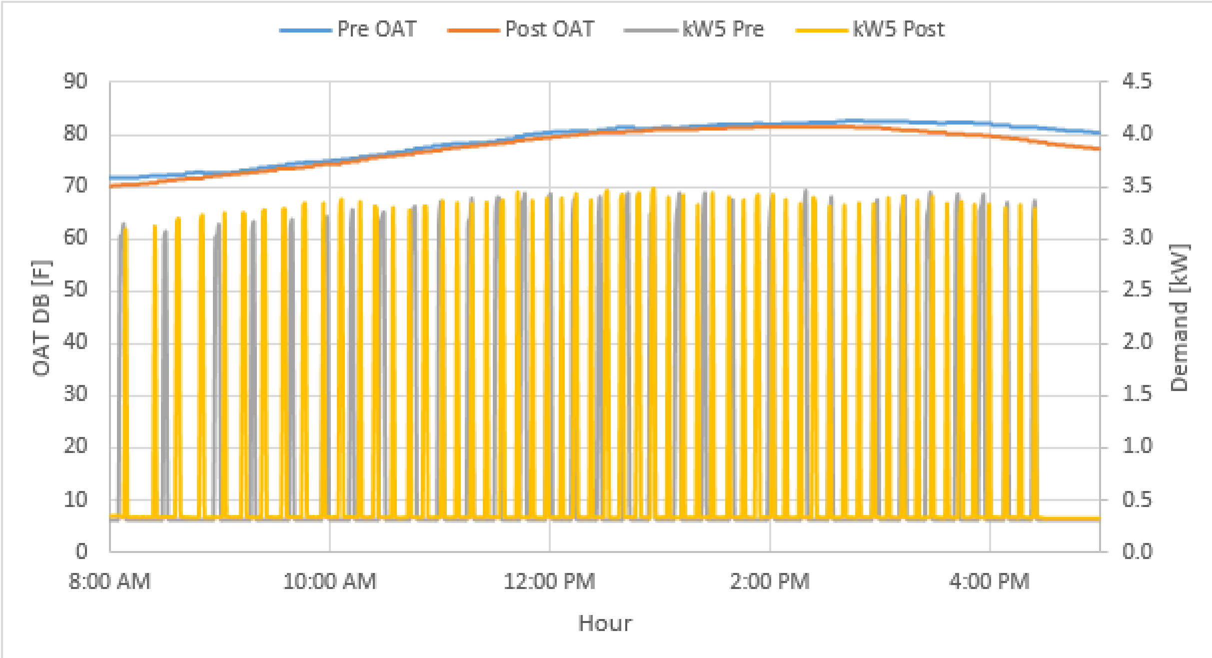
EL CAJON SITE

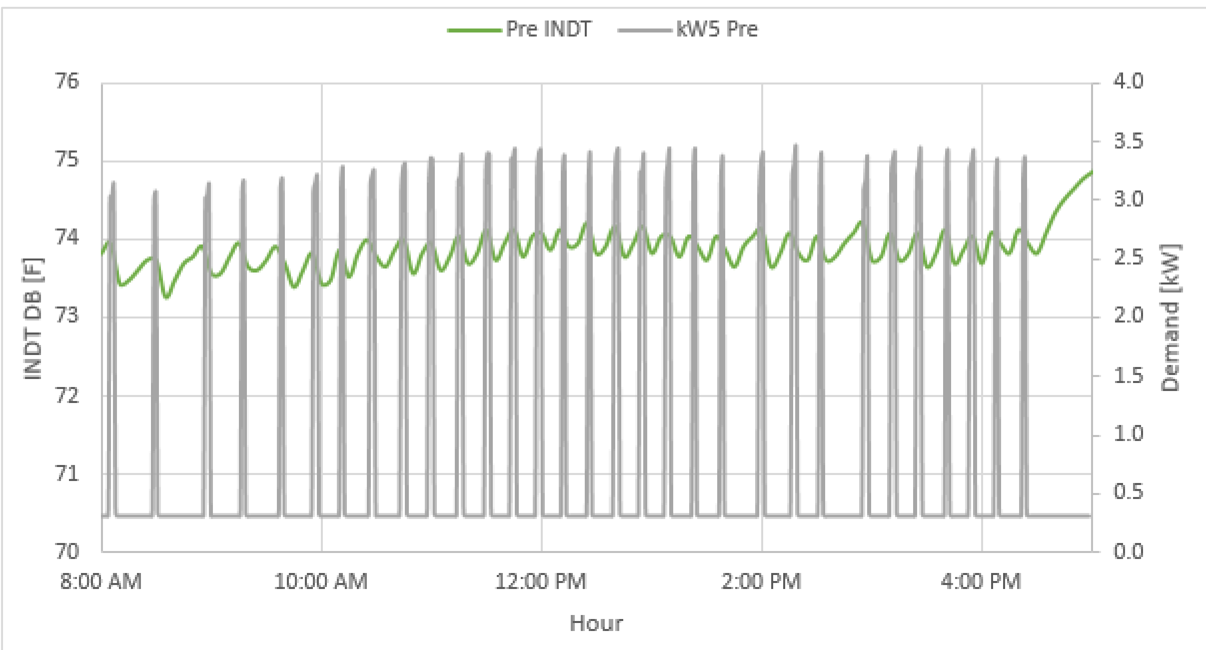
AC5

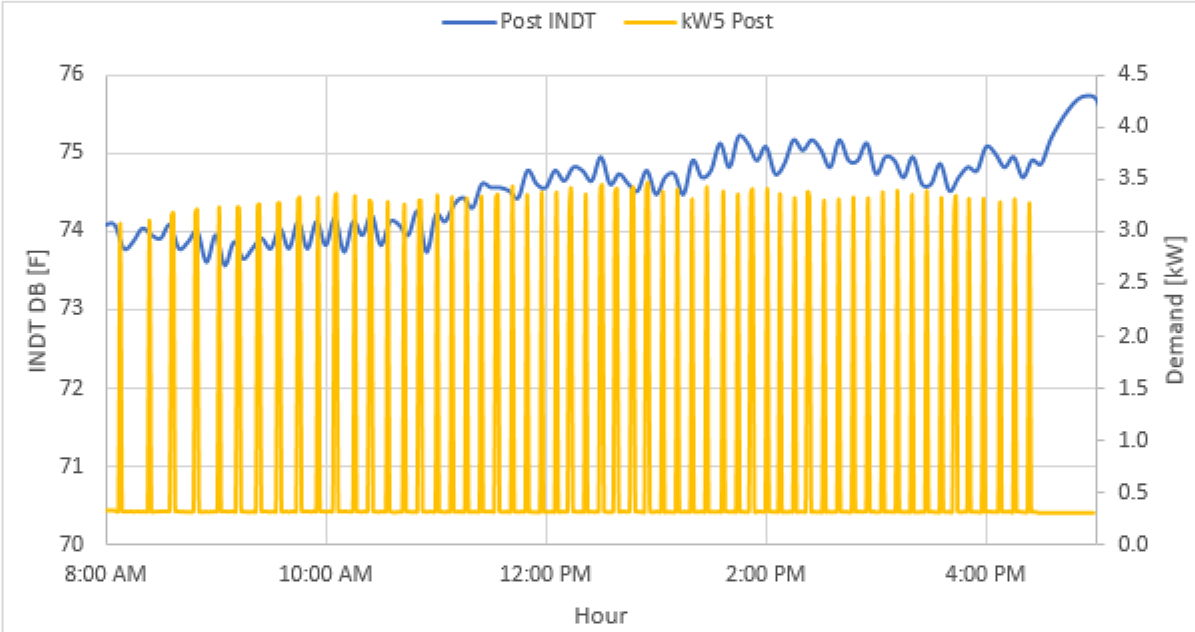
AC5 conditioned an office. The regression analysis showed a slightly increase in hourly average demand. The average hourly space temperature showed slightly higher afternoon temperatures after the technology implementation. The number of cycling increased greatly after the retrofit, with the unit cycling for 31 time during baseline and 57 times on similar weather days.





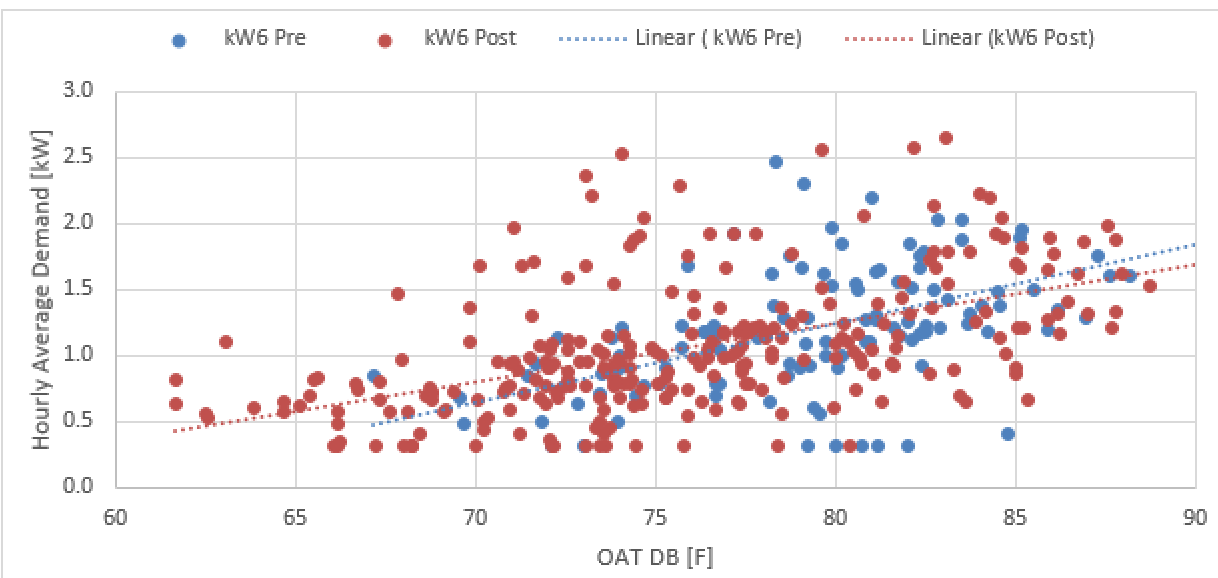

Pre OAT
Post OAT
kW5 Pre
kW5 Post
OAT DB [F]
Demand [kW]
Hour
90
80
70
60
50
40
30
20
10
0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM

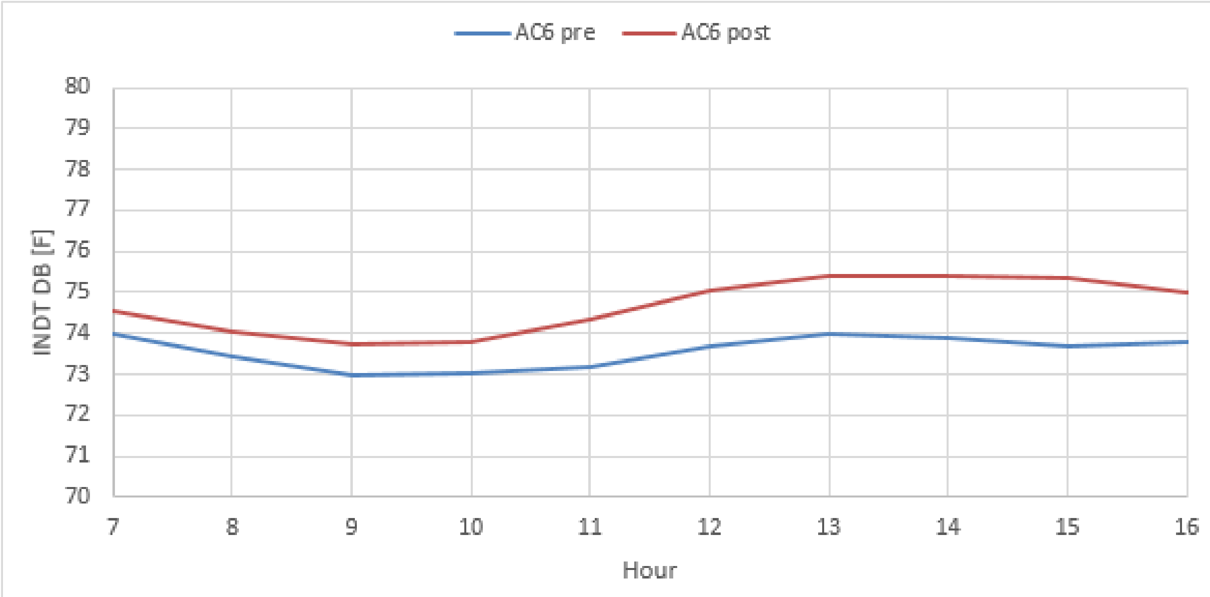

Pre INDT
kW5 Pre
INDT DB [F]
Demand [kW]
Hour
76
75
74
73
72
71
70
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM

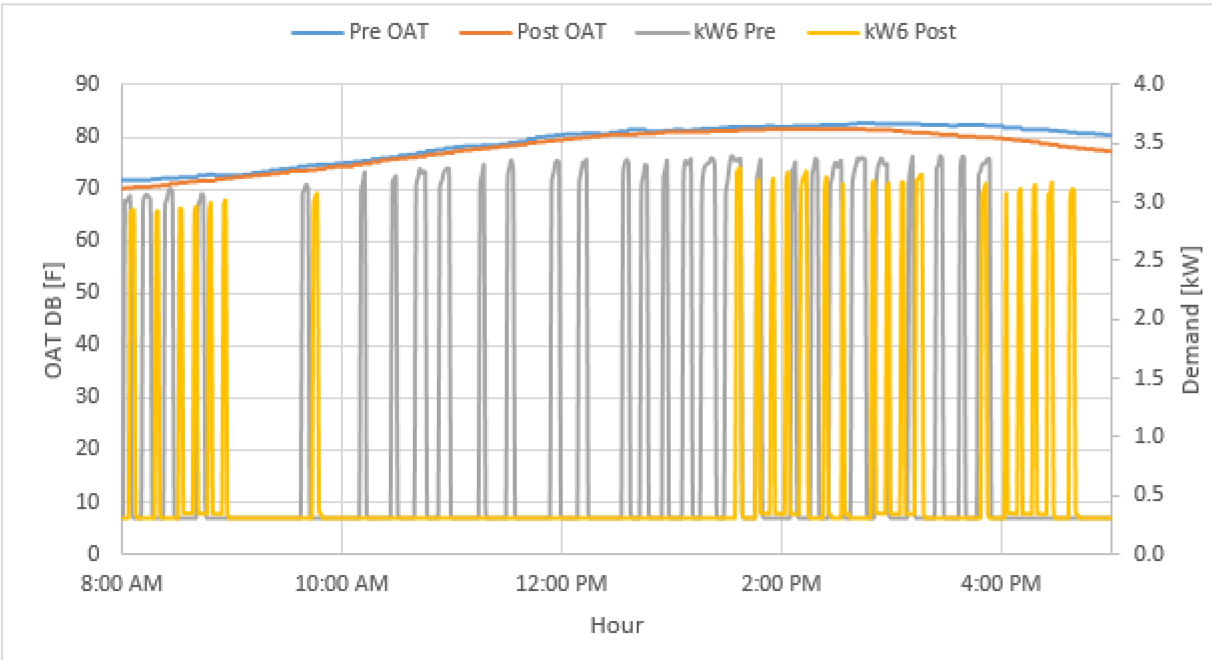


AC6

AC6 air-conditioned an office kitchen/lounge. The regression analysis showed no significant change in hourly average demand although average hourly space temperature increased slightly after the retrofit. The number of cycling decreased after the retrofit, with the unit cycling for 29 time during baseline and 24 times on similar weather days. The increased average hourly space temperature and reduced cycling during mid-day data may be an indication that the temperature setpoint was increased by one or two degrees, causing the unit to cycle on less during the post period.

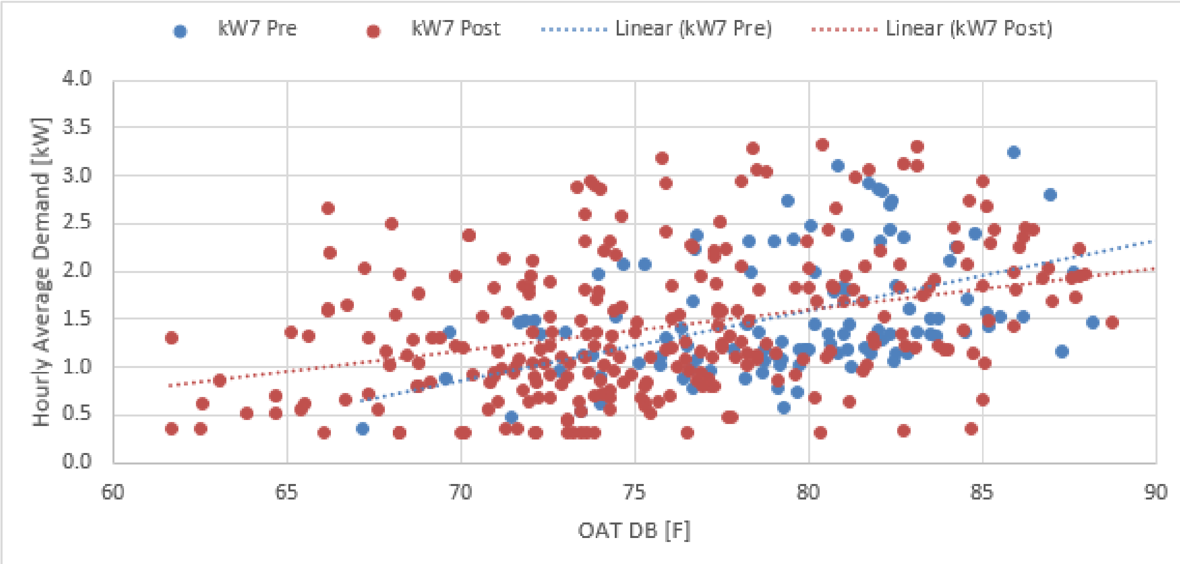


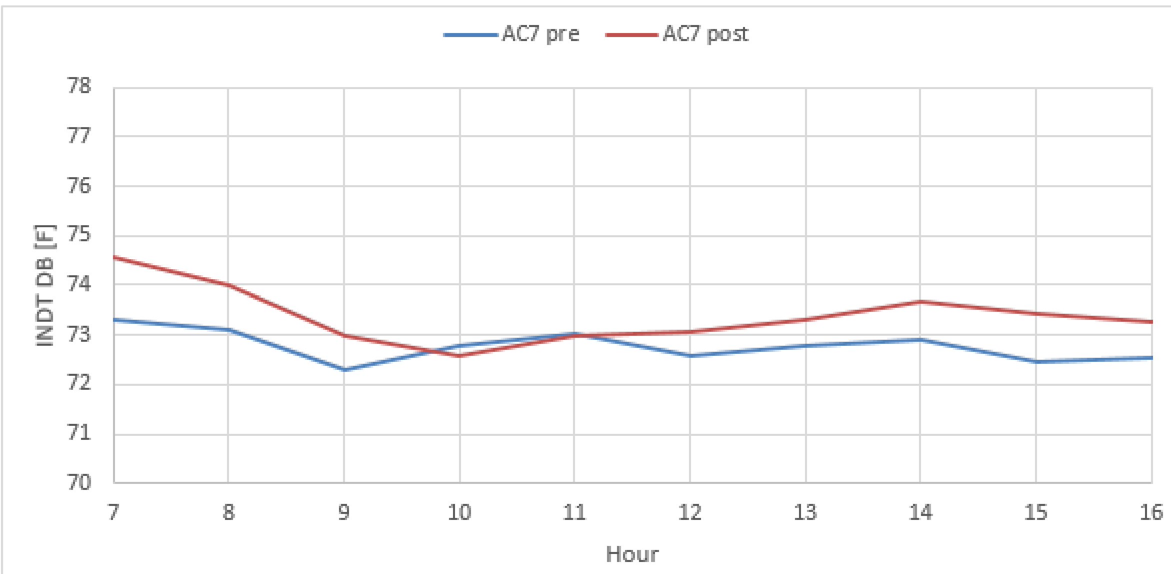


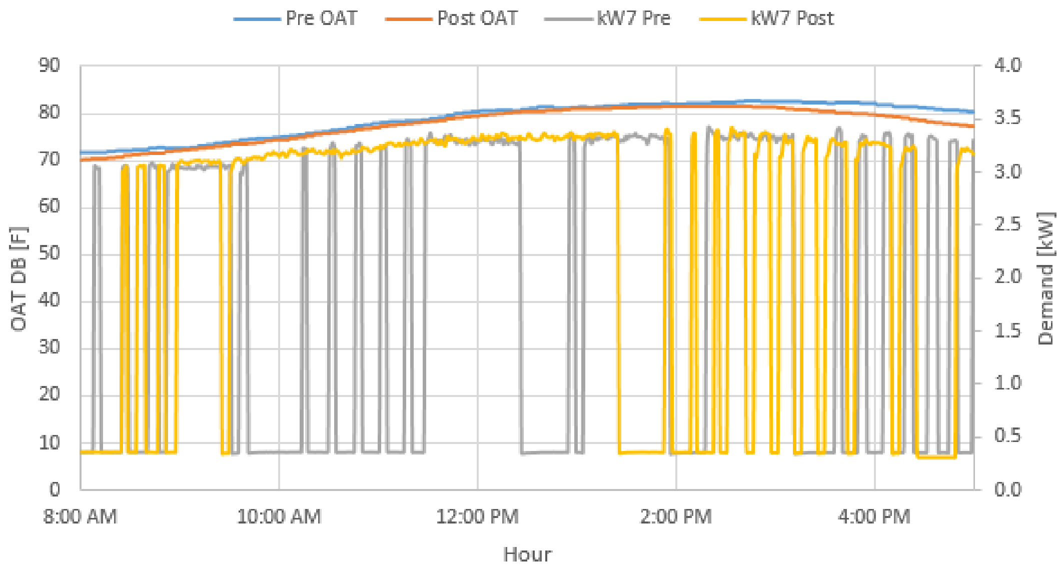


AC7

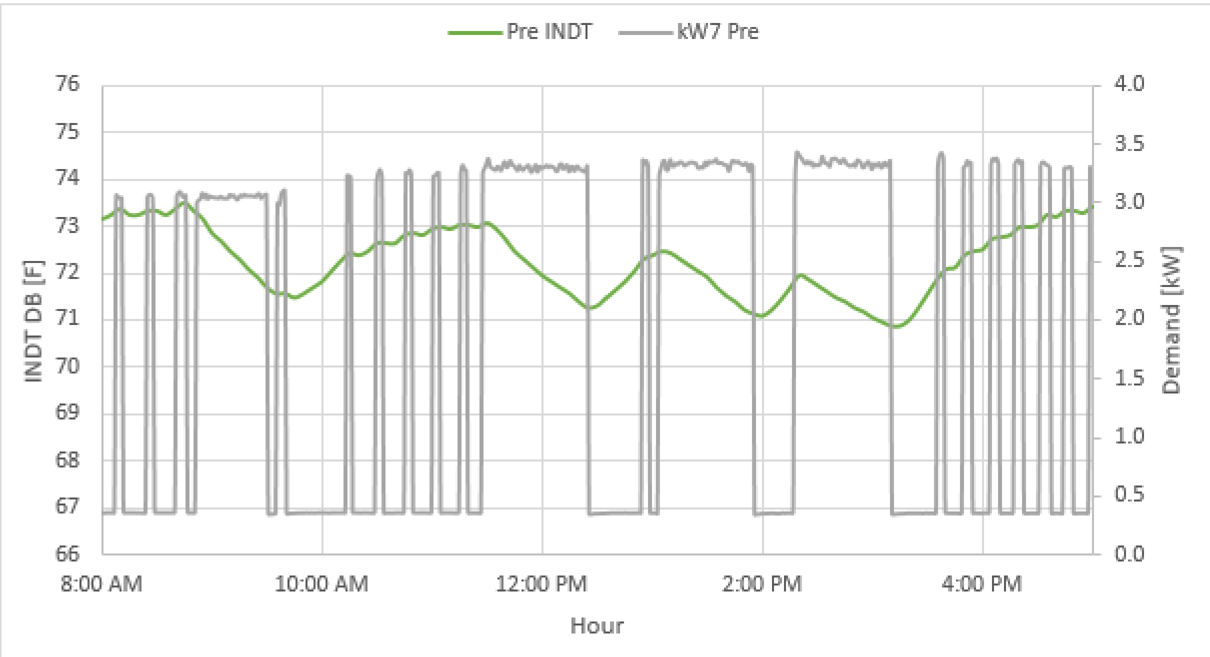
AC7 served offices with its thermostat located in a small office. The regression analysis showed no significant change in hourly average demand. The average hourly space temperature was kept relatively constant before and after the retrofit, with slightly higher temperatures in the early morning and late afternoon after the technology implementation. The number of cycling decreased after the retrofit, with the unit cycling for 20 time during baseline and 16 times on similar weather days.

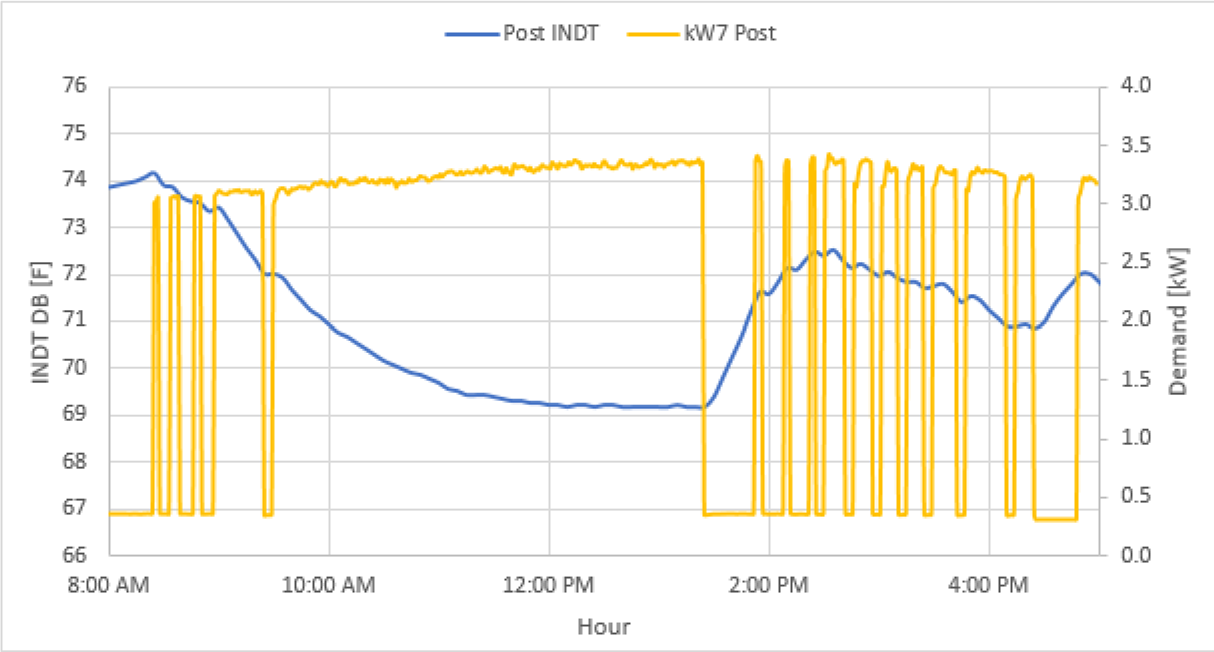

kW7 Pre
kW7 Post
Linear (kW7 Pre)
Linear (kW7 Post)
Hourly Average Demand [kW]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
60
65
70
75
80
85
90
OAT DB [F]


AC7 pre
AC7 post
INDT DB [F]
78
77
76
75
74
73
72
71
70
7
8
9
10
11
12
13
14
15
16
Hour



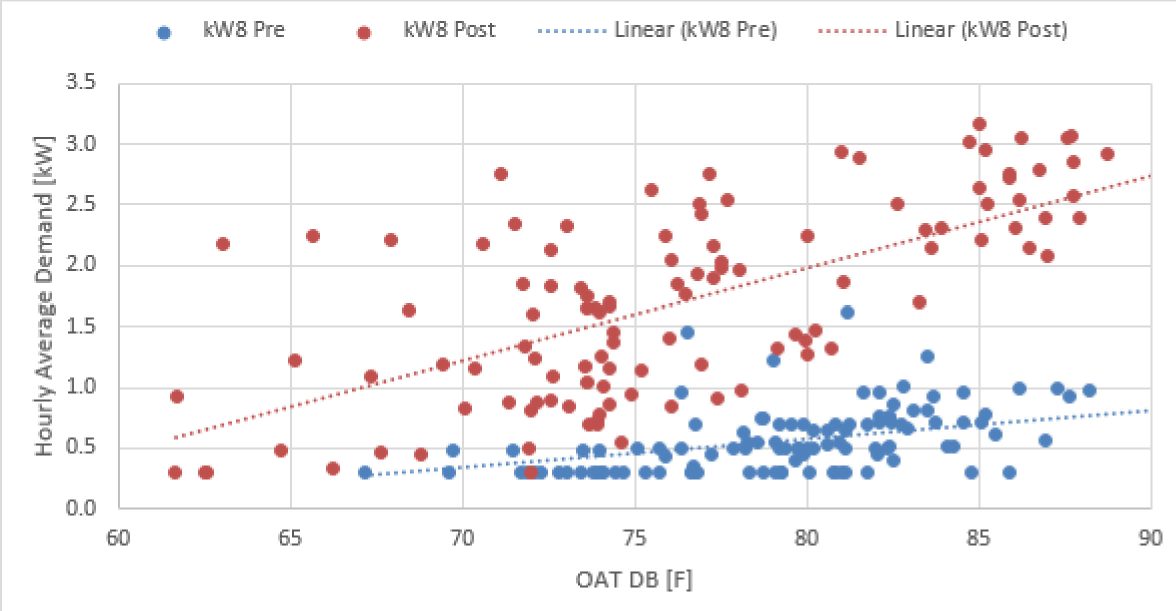
Below figures show the indoor space temperature for the two days compared. It appears that the space temperature setpoint was changed lower than when the controller was initially installed. Because the thermostat is located an office and easily accessible, the setpoint may have been changed frequently.

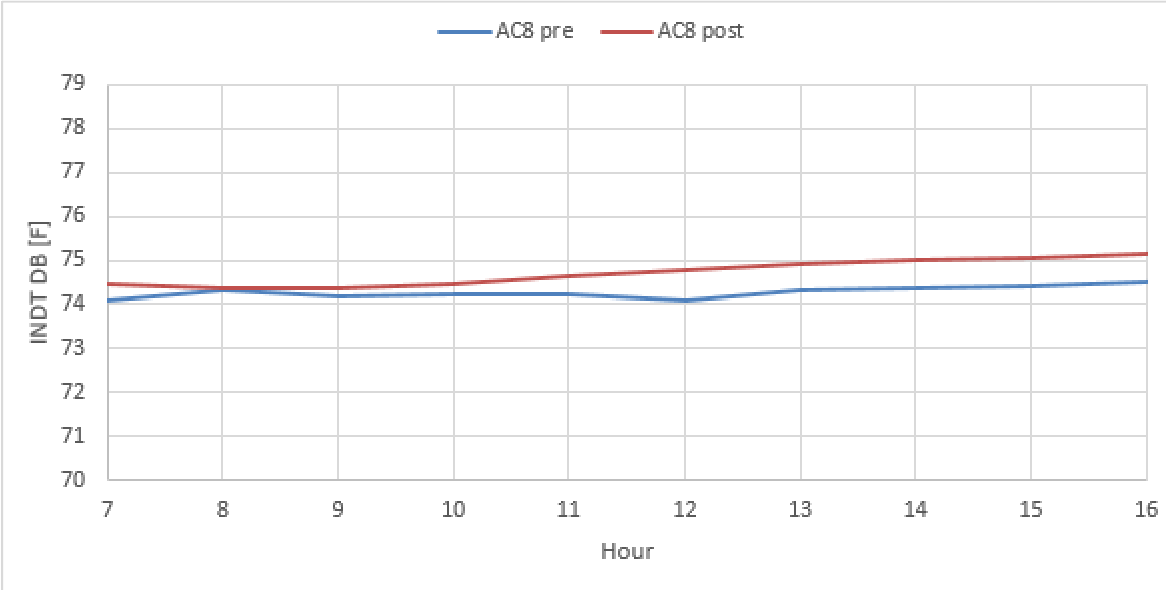


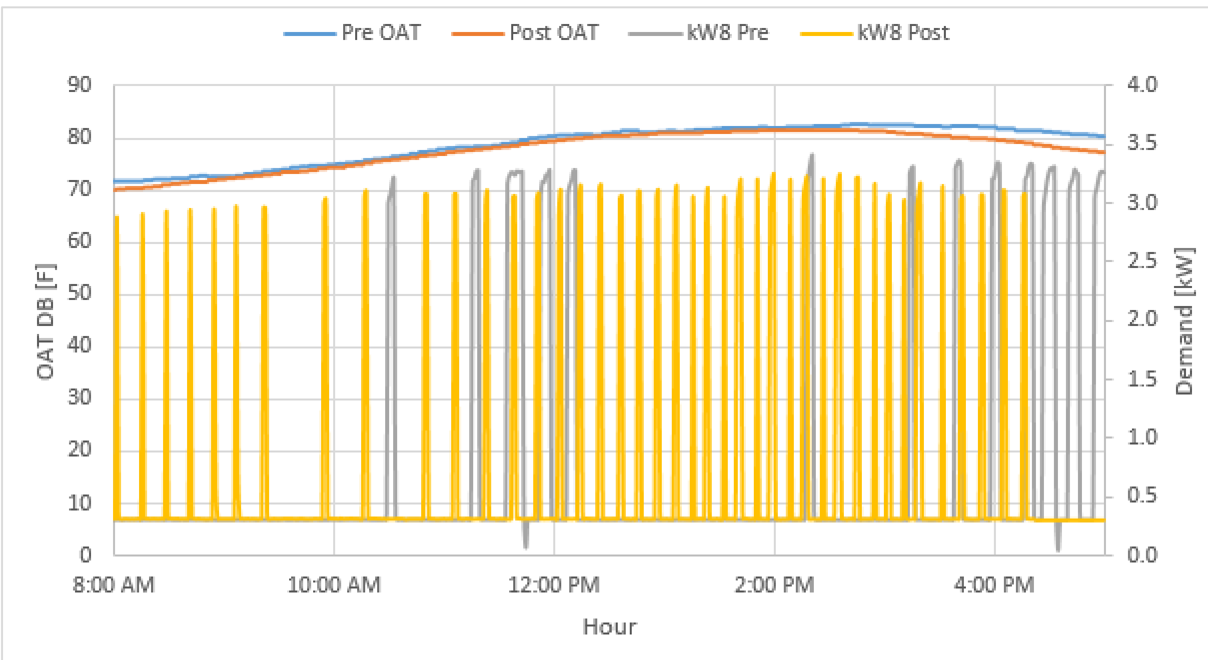


AC8

AC8 also served an office with cubicles with thermostat located in the middle of the room. The regression analysis showed great increase in hourly average demand. The average hourly space temperature was kept relatively constant before and after the retrofit, with slightly higher temperatures in the afternoon after the technology implementation. The number of cycling also increased after the retrofit, with the unit cycling for 13 time during baseline and 41 times on similar weather days.







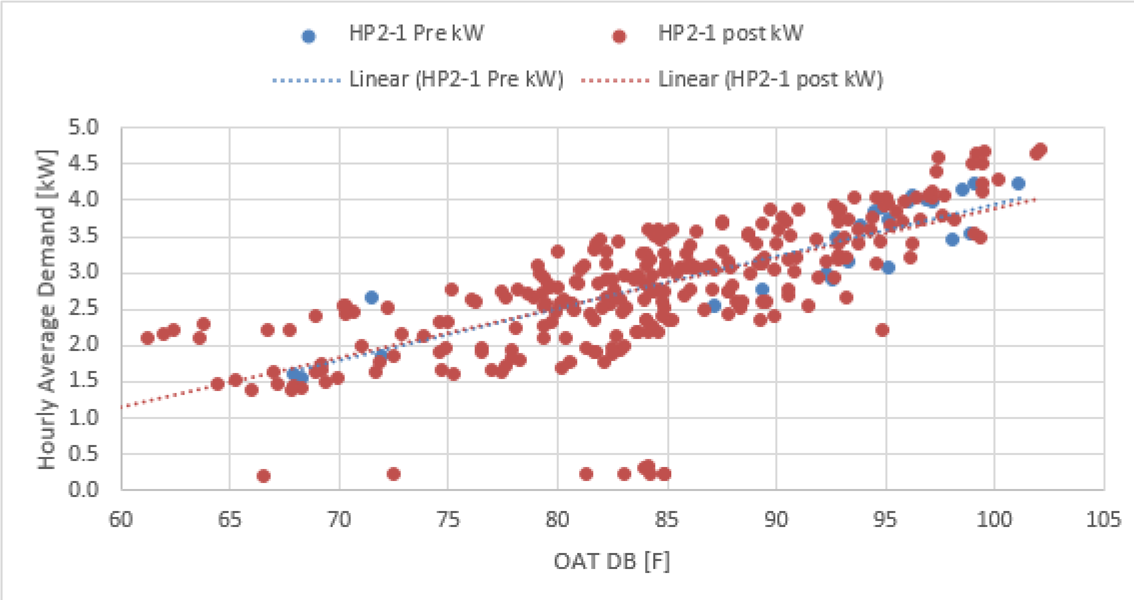
AC9

AC 9 was removed from the analysis due to technical difficulties experienced during the installation. The controller was not installed properly and therefore the collected data does not represent the operation of the technology.

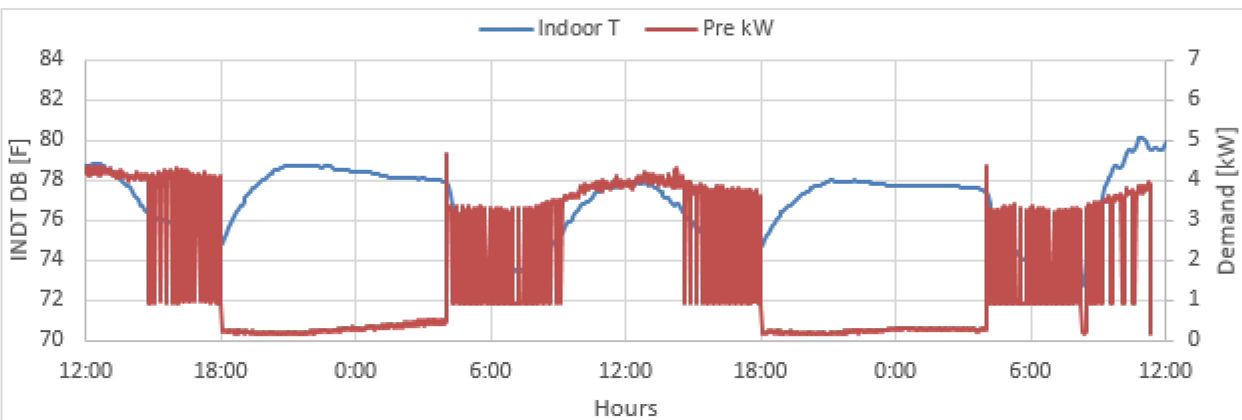
POWAY SITE

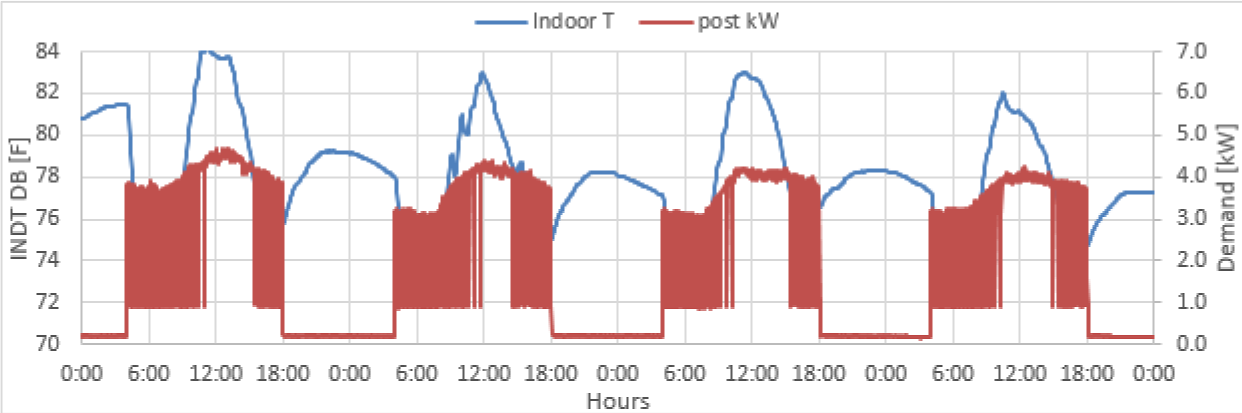
PHP2-1

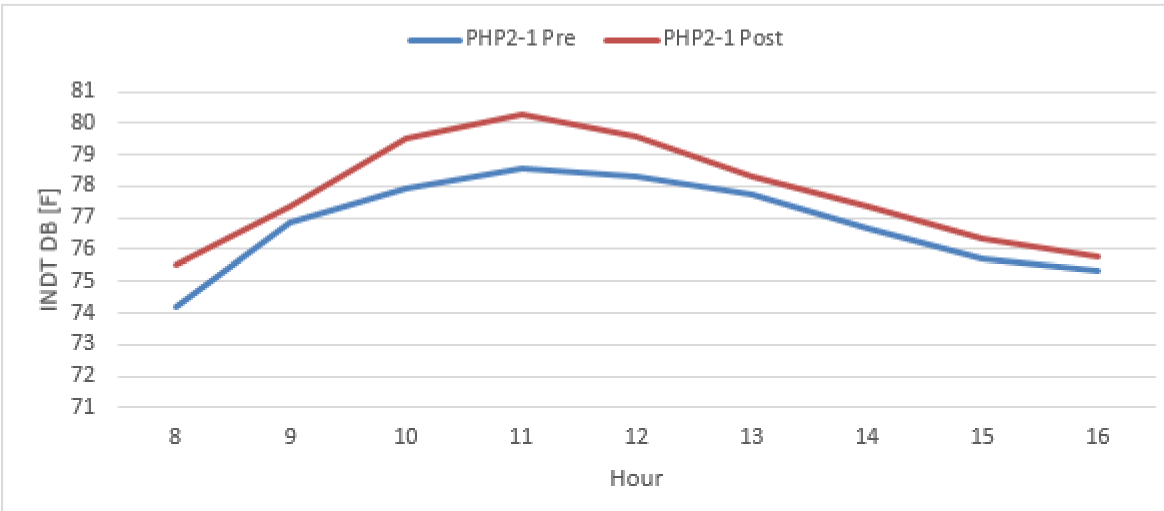
PHP2-1 served reception area with large windows on the south wall. The regression analysis showed that no change had occurred in hourly average demands before and after the technology implementation.



The minute by minute data showed that the unit ran continuously during the day in both baseline and post-implementation periods, indicating that the unit was undersized. The average hourly space temperatures increased after the retrofit, with space temperature reaching as high as 84°F as shown in figures below. The receptionist also stated that the room got hot during the day, confirming the unit was not able to meet the load. Note only two days' worth of baseline data was collected for this unit due to bad sensor.

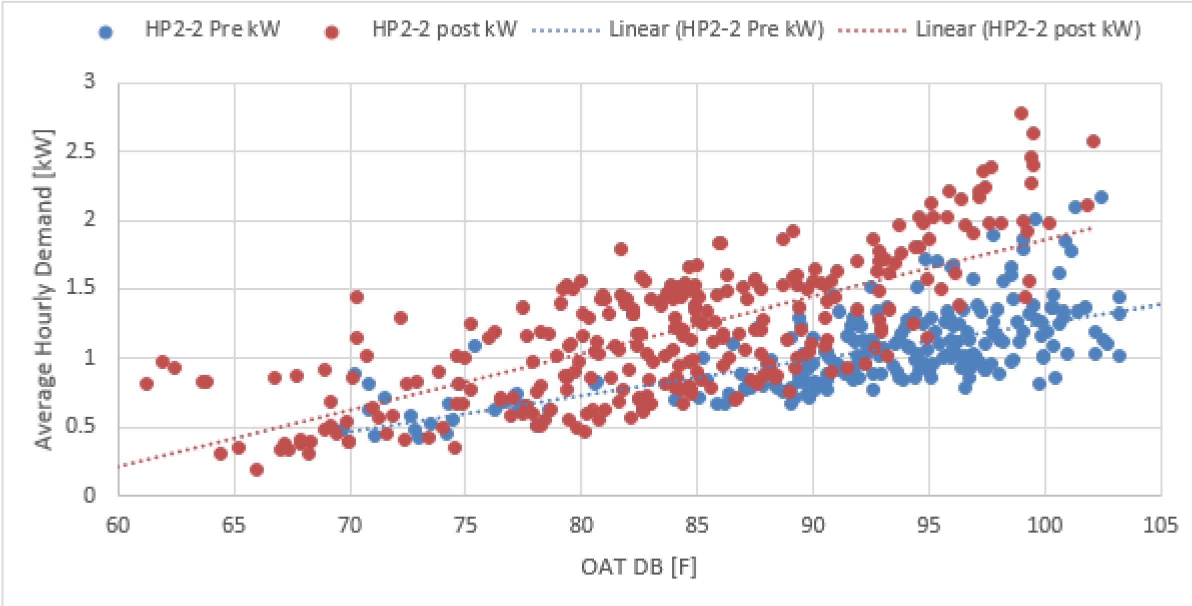


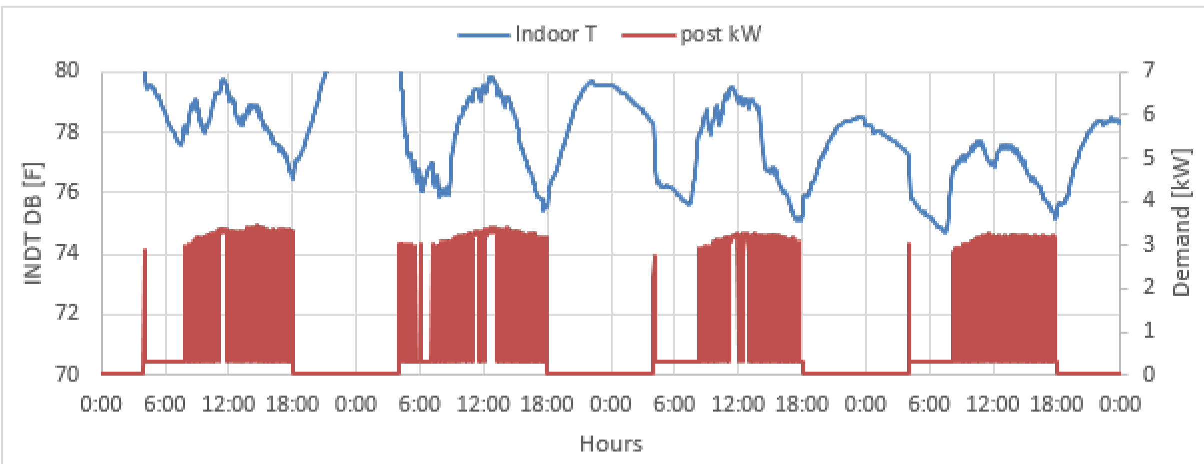


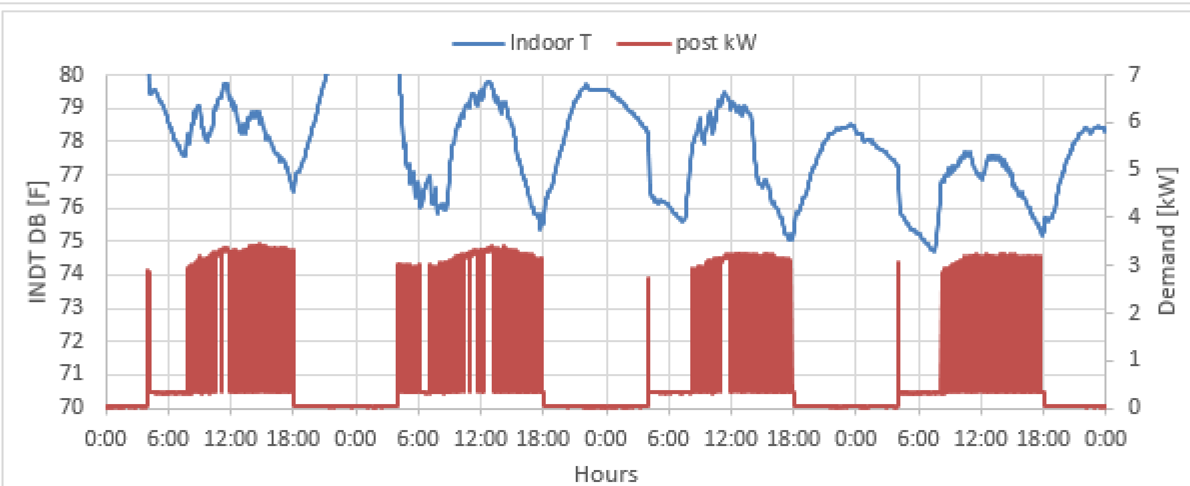


PHP2-2

PHP2-2 served a conference room that also has large windows on the south wall. The temperature logger may have not read the space temperature correctly as the space temperature floated up in both periods during the day while compressor cycled off frequently. Regression analysis showed that the hourly average demand was slightly higher during the post. Note that the baseline data was modified to include fan power during occupied period as the raw data showed that the fan was not on.

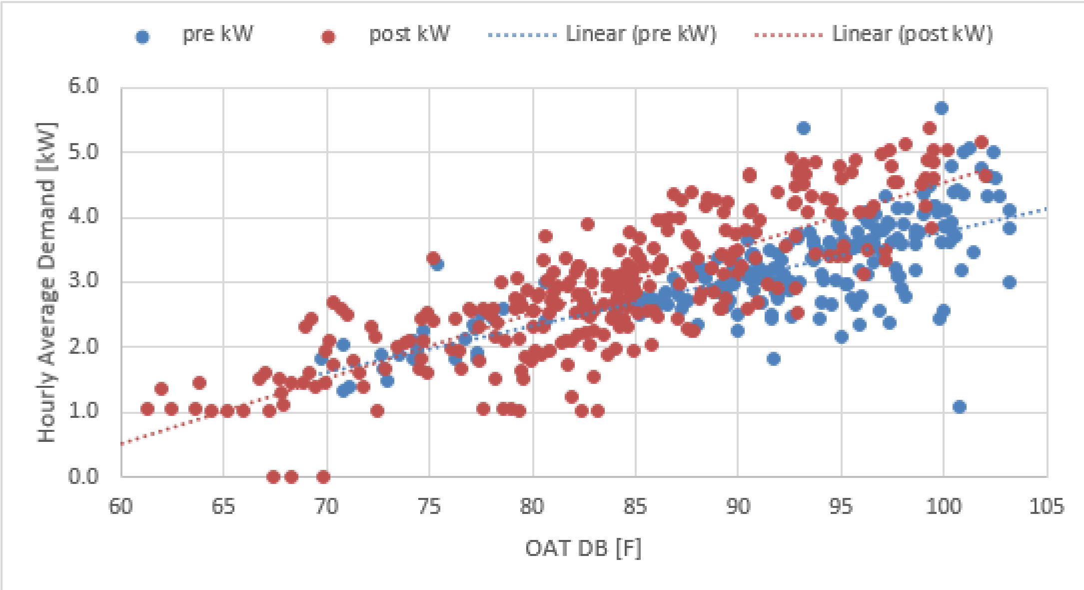

HP2-2 Pre kW
HP2-2 post kW
Linear (HP2-2 Pre kW)
Linear (HP2-2 post kW)
Average Hourly Demand [kW]
OAT DB [F]


Indoor T
post kW
INDT DB [F]
Demand [kW]
Hours

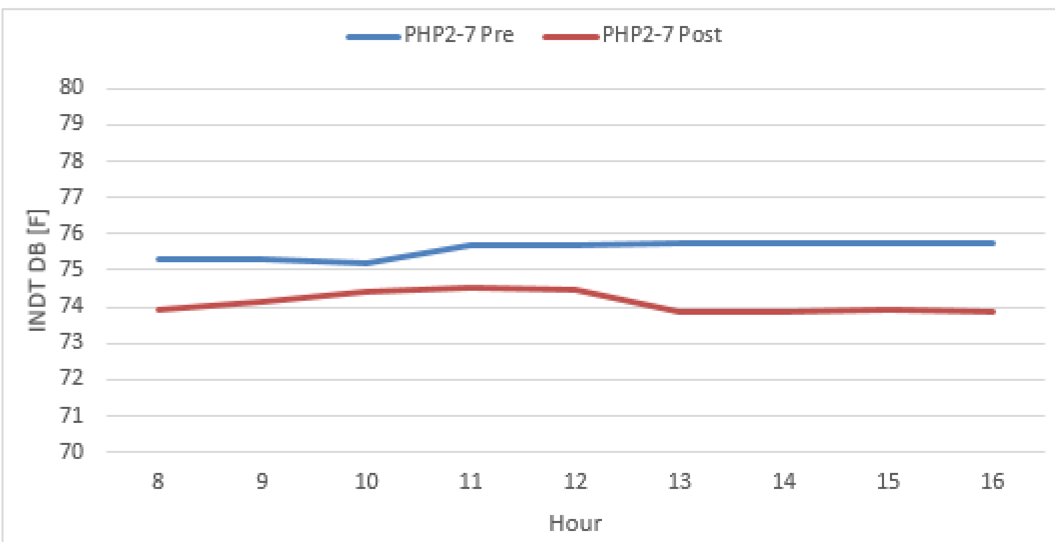

Indoor T
post kW
INDT DB [F]
Demand [kW]
Hours

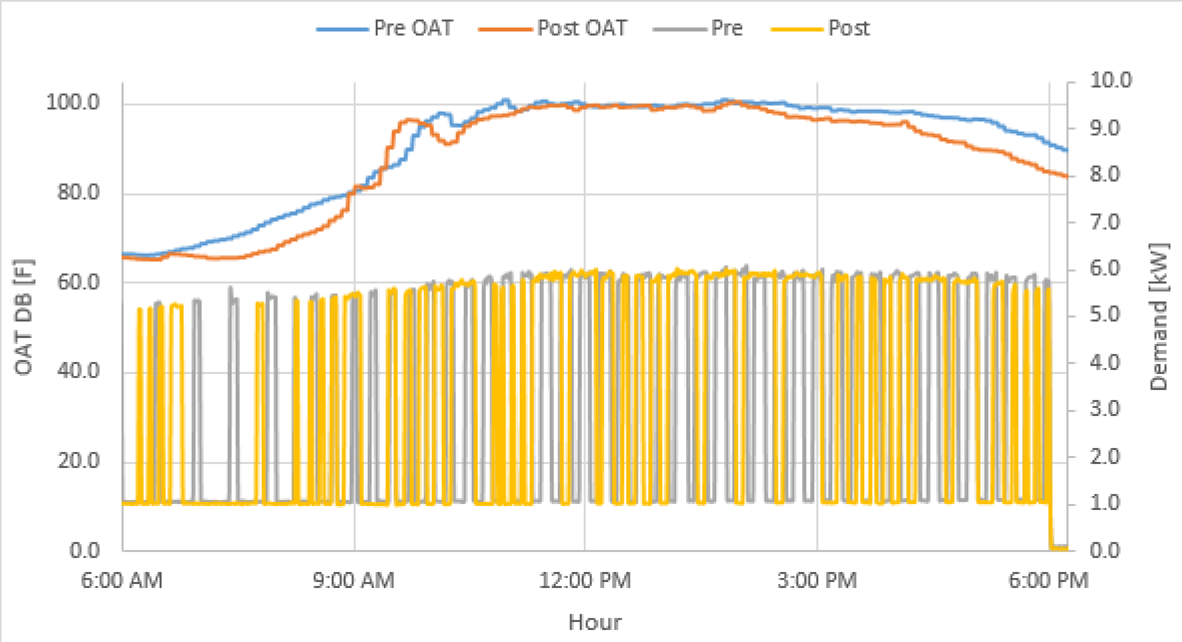
PHP2-7 & PHP2-8

PHP2-7 and PHP2-8 are both used to air condition a large conference room. However, PHP2-8 didn't turn on and only PHP2-7 operated during the monitoring periods. The regression analysis of the PHP2-7 unit below shows slight increase in energy consumption during post period.

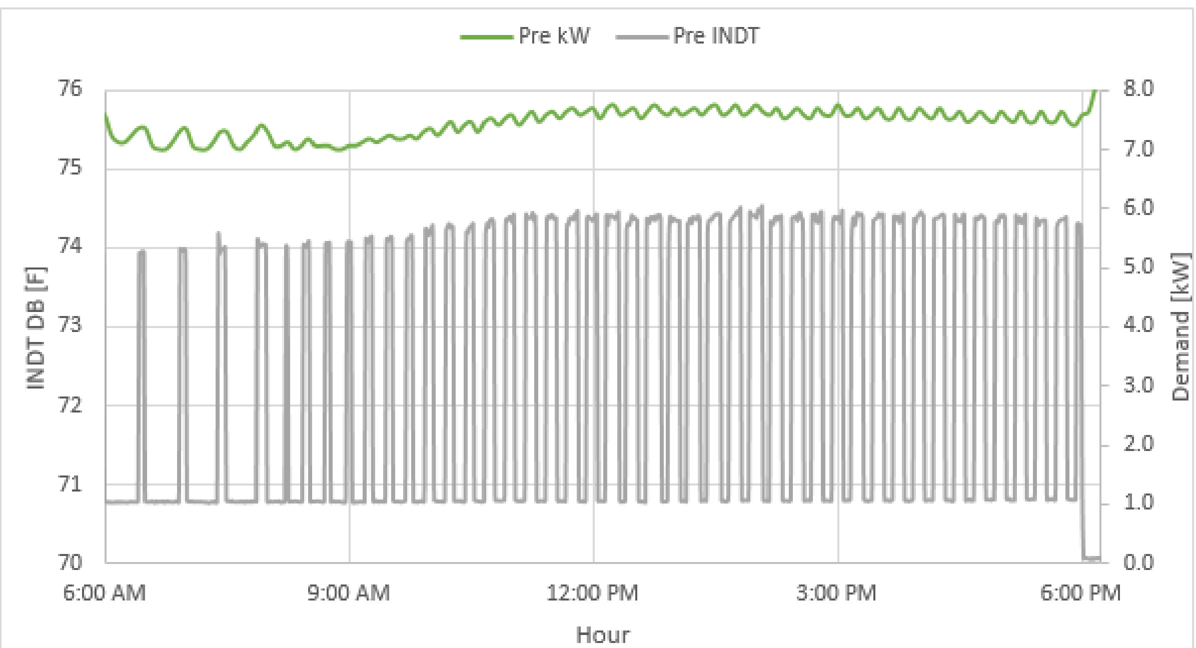


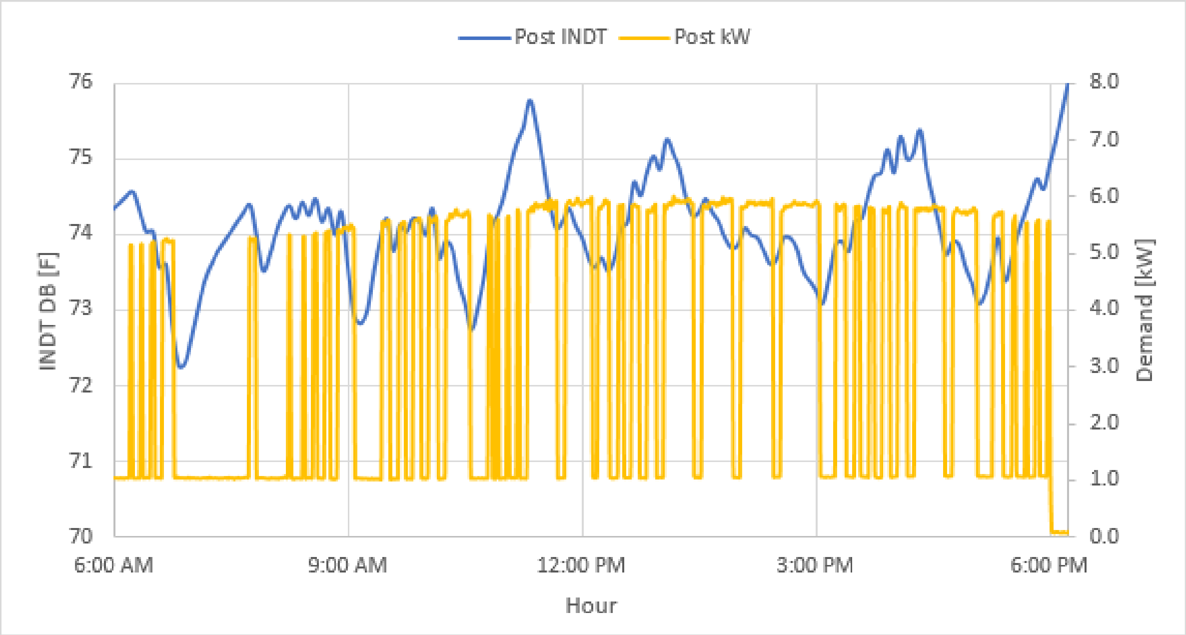
The space temperature decreased in the post by approximately 1.5°F. The unit operation on similar weather days showed that the unit cycled 44 times during the baseline and 42 times during post period.





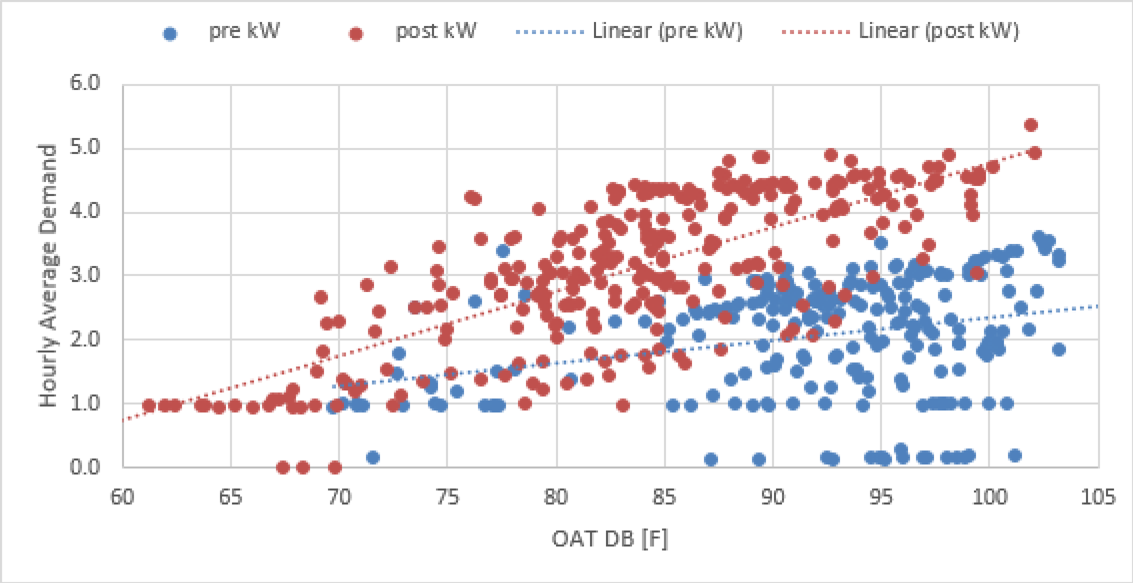
The difference in control strategy before and after the retrofit is clearly illustrated in below figures. The space temperature was allowed to drift on broader band (as much as ±2°F) compared to baseline where temperature was kept within 1°F of setpoint.

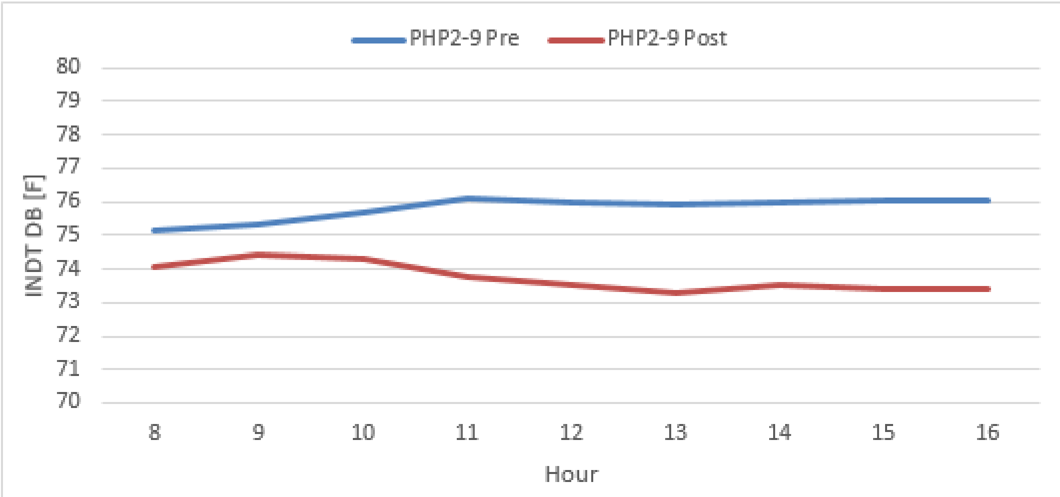


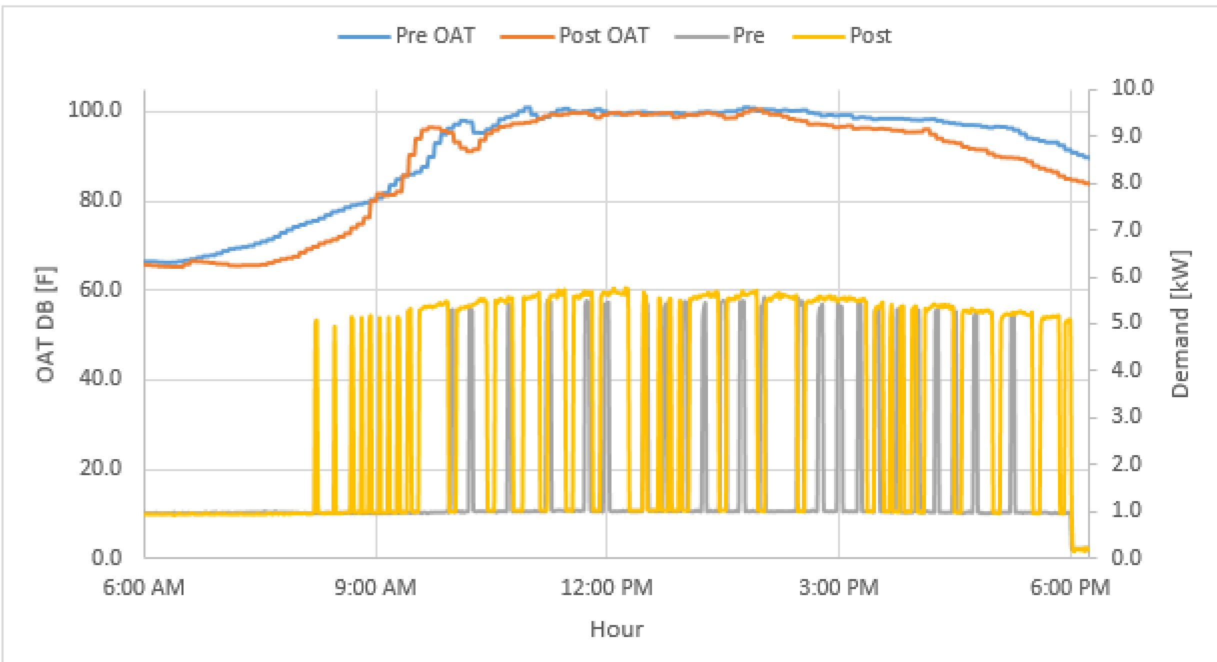


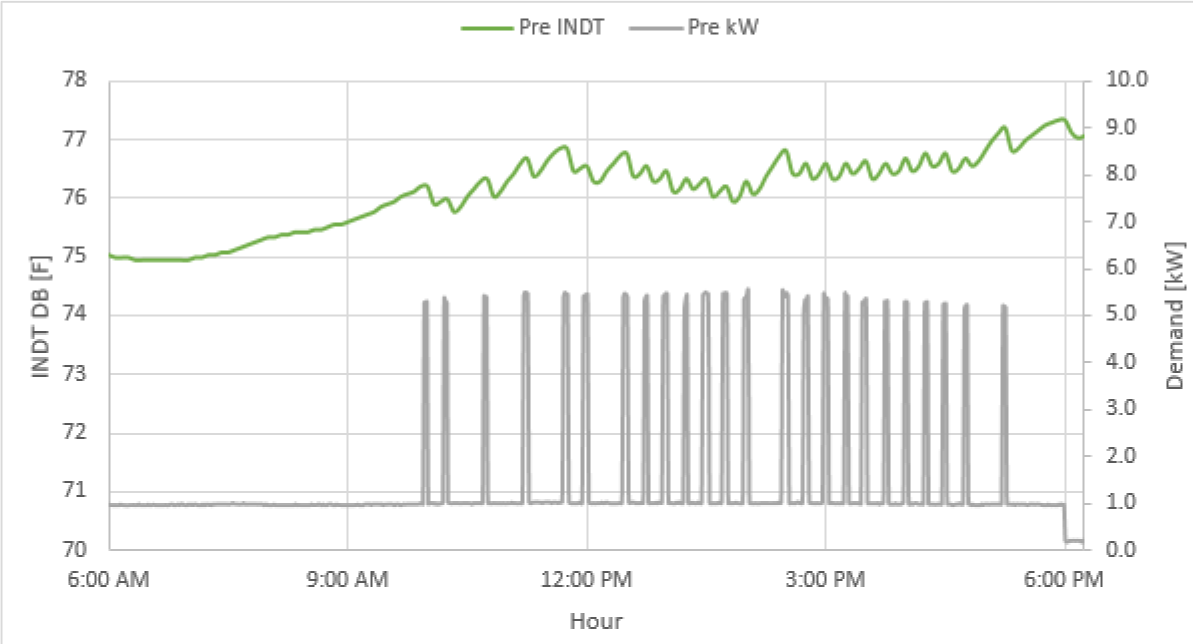
PHP2-9

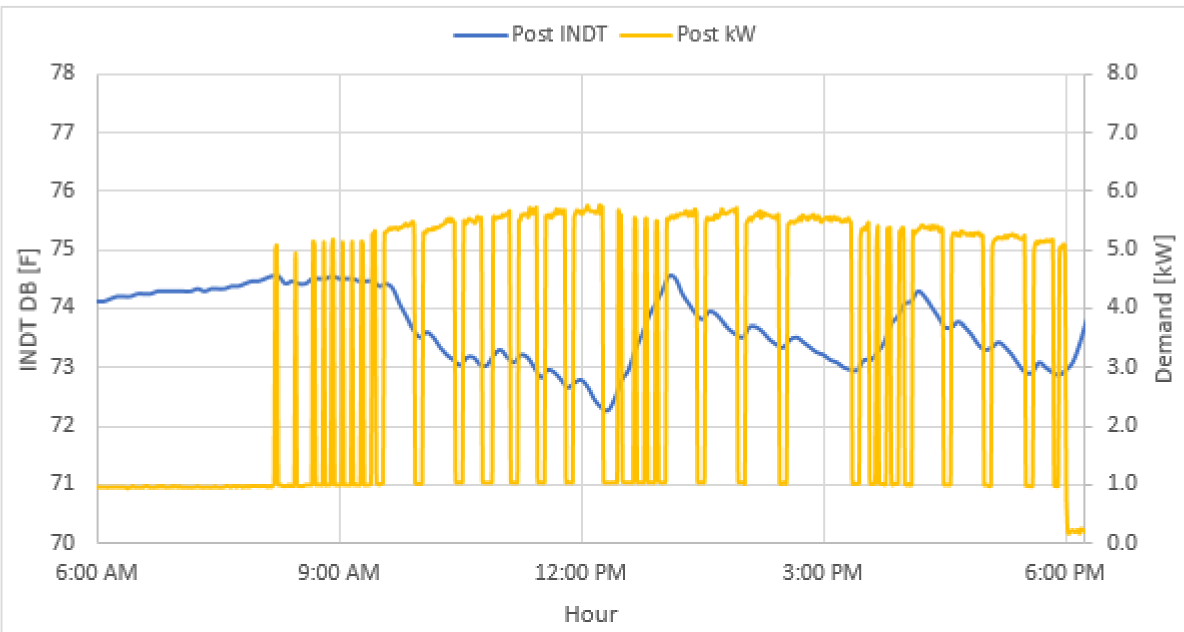
PHP2-9 conditions offices with its thermostat located in a small office. The regression analysis showed an increase in hourly average demand. However, there was also a relatively large decrease in average hourly temperature of the space in the post period. Since the thermostat is located in the office and accessible, it is possible that the temperature setpoint was lowered during the course of study.




PHP2-9 Pre
PHP2-9 Post
INDT DB [F]
80
79
78
77
76
75
74
73
72
71
70
8
9
10
11
12
13
14
15
16
Hour


Pre OAT
Post OAT
Pre
Post
OAT DB [F]
100.0
80.0
60.0
40.0
20.0
0.0
Demand [kW]
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour


Pre INDT
Pre kW
INDT DB [F]
Demand [kW]
78
77
76
75
74
73
72
71
70
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour

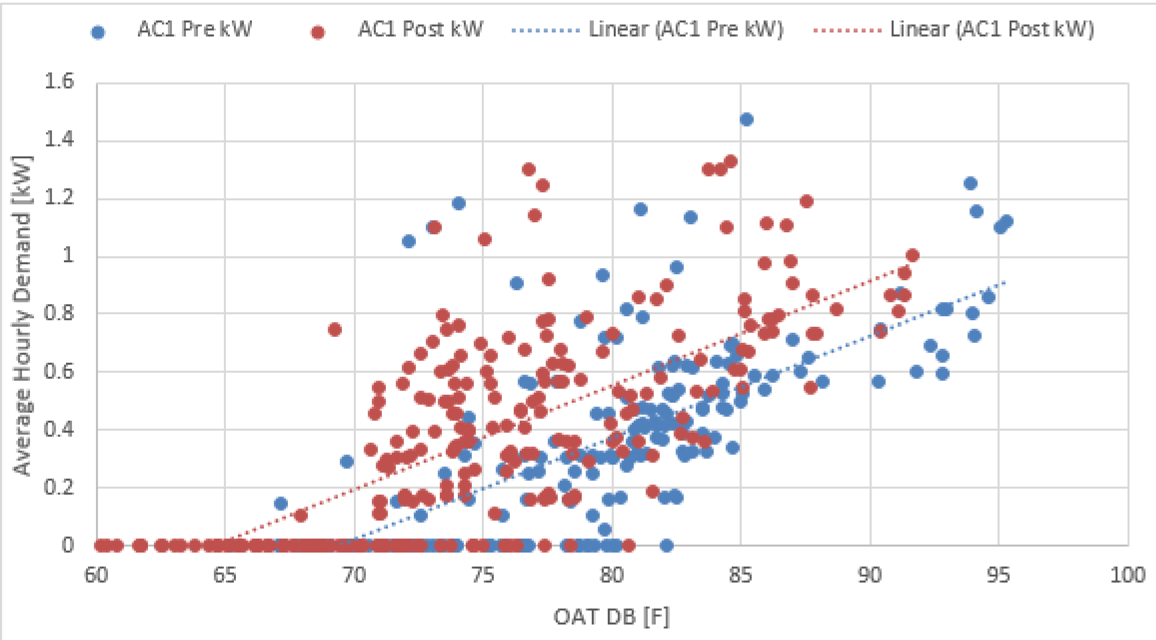

Post INDT
Post kW
INDT DB [F]
Demand [kW]
78
77
76
75
74
73
72
71
70
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour

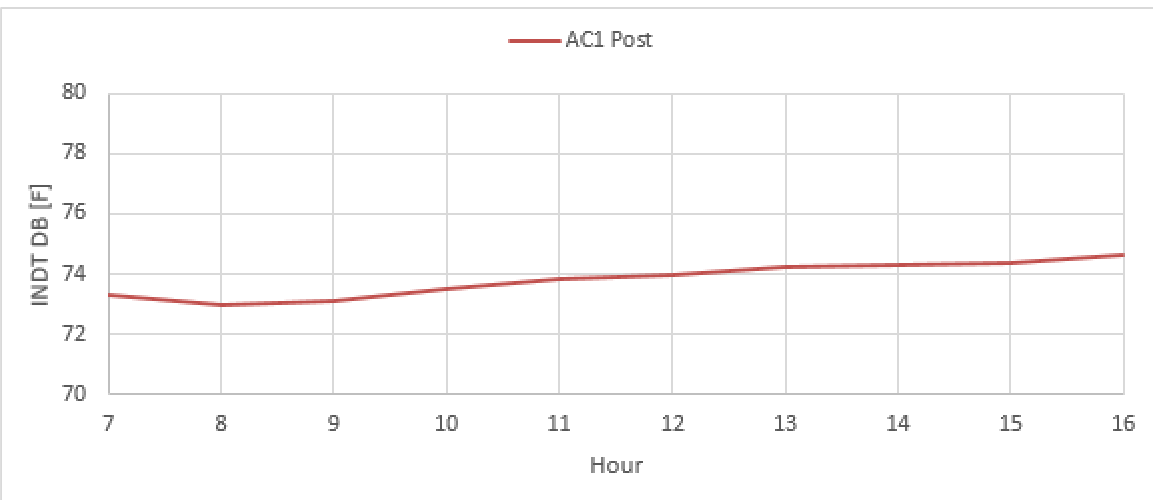
APPENDIX 2: PHASE 1 - CONTROLLER B UNIT BY UNIT ANALYSIS

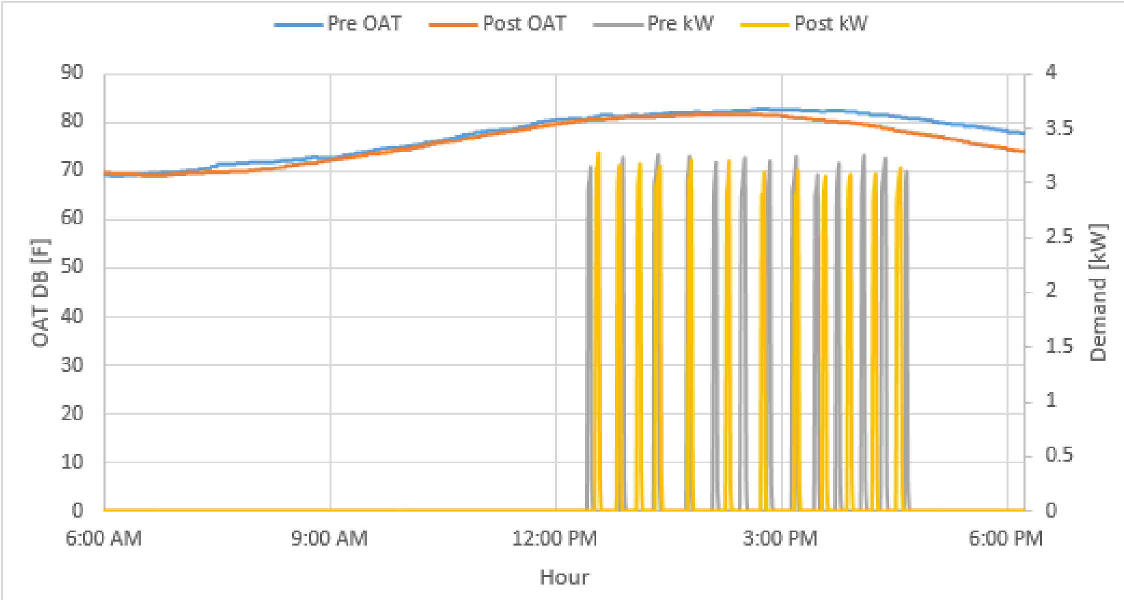
EL CAJON SITE

AC1

Unit AC1 served a conference room and was lightly loaded with the averaged compressor loading of 15%. The average hourly demand increased slightly after the retrofit, but the difference is very small (less than 0.2 kW) and within the margin of error. The space temperatures before the installation were not collected for this room because the logger was placed in another room, which was thought to be served by this unit. There was no significant change in unit's cycling operation.

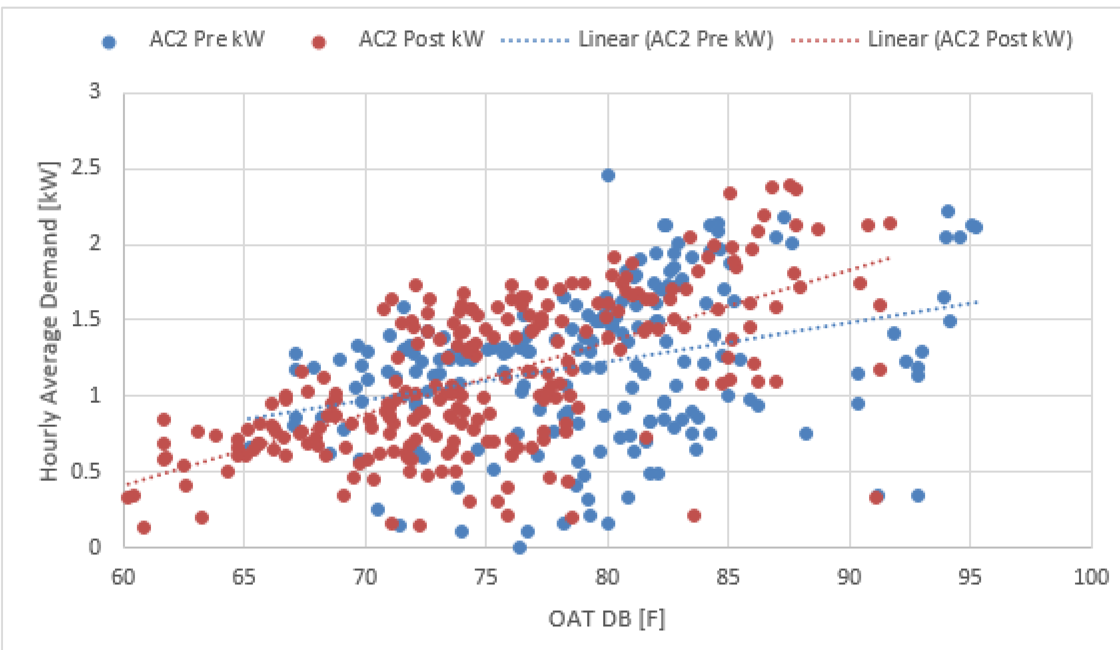


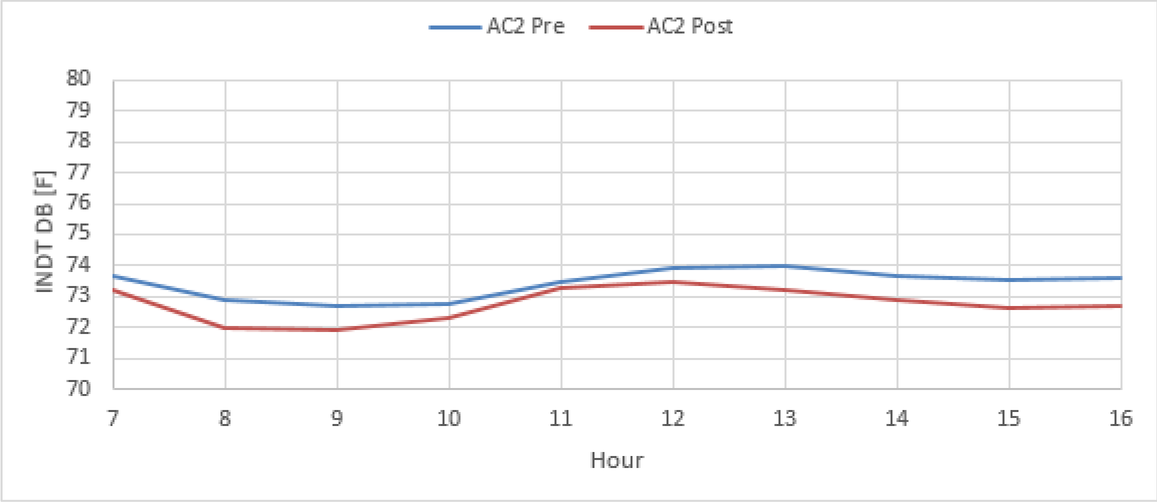


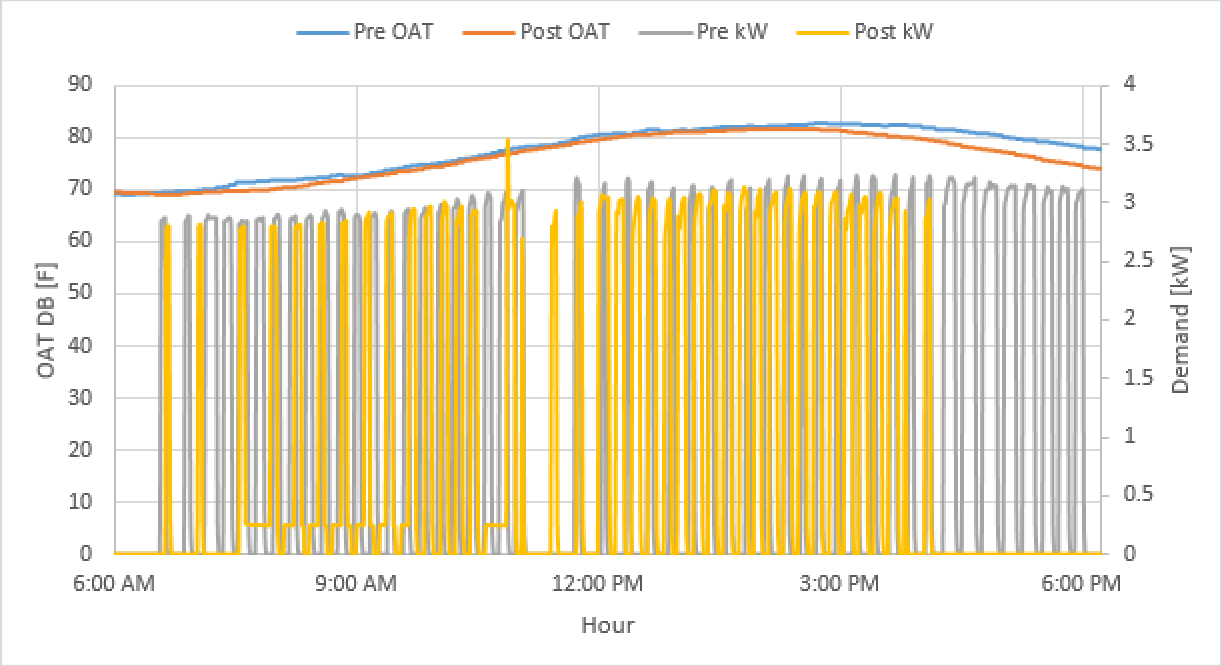


AC2

No significant change in energy consumption was found for unit AC2, which served an office. The space temperature was also kept relatively constant before and after the installation. The data showed somewhat more cycling at higher OAT and less cycling at lower OAT.

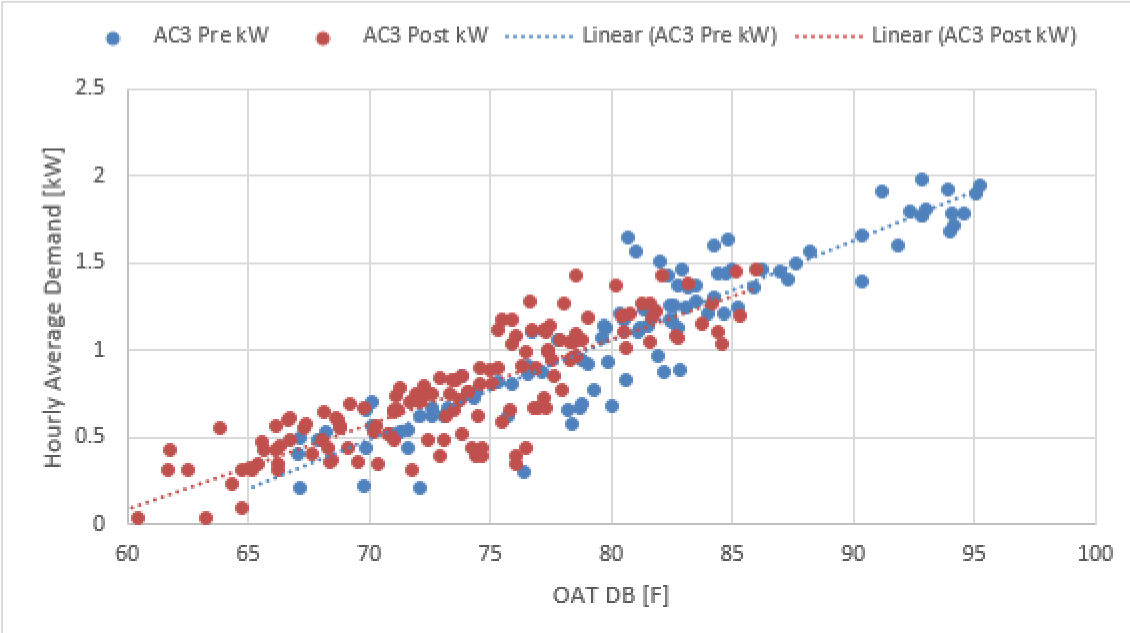


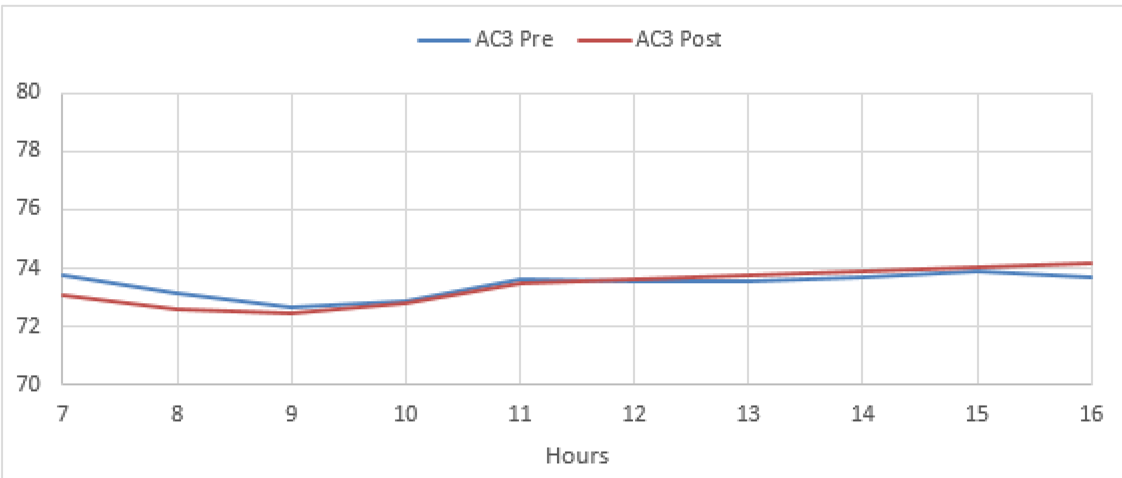




AC3

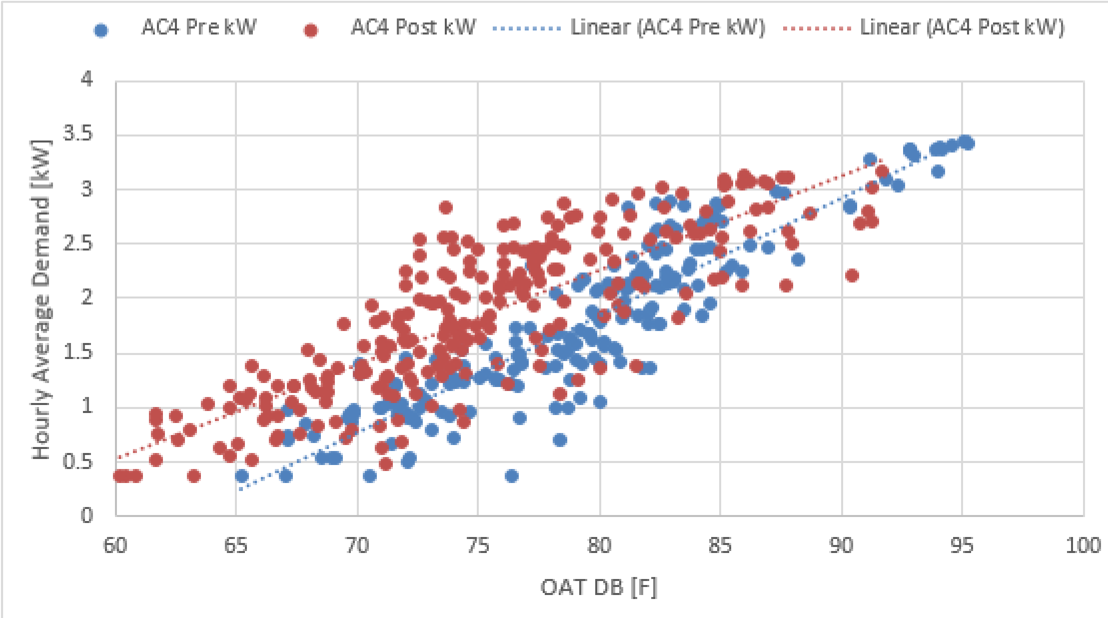
No change in energy consumption was observed for the unit AC3 serving an office. For this unit, the post period starting the week of 9/19 was disregarded due to inconsistency found in the data. The space temperature was kept between 73°F and 74°F for both periods.

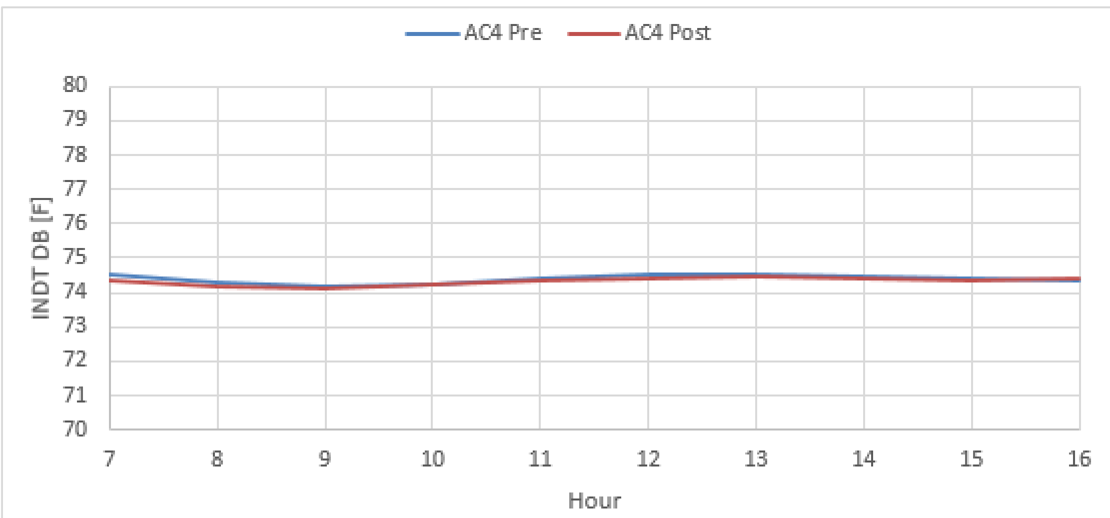


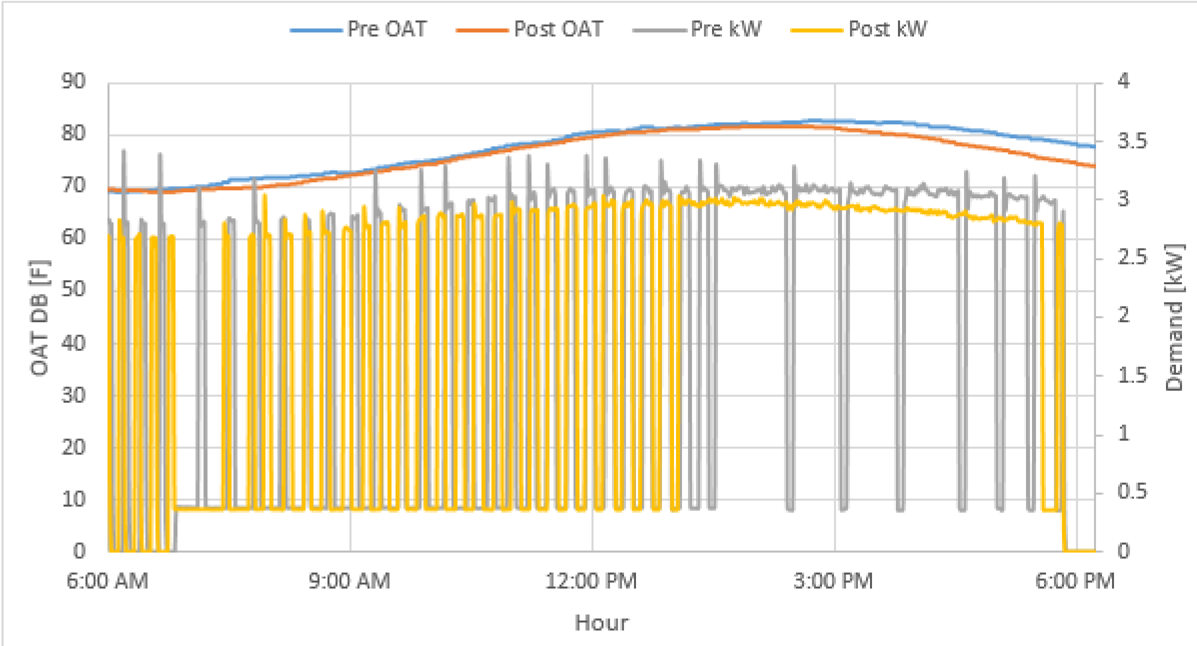


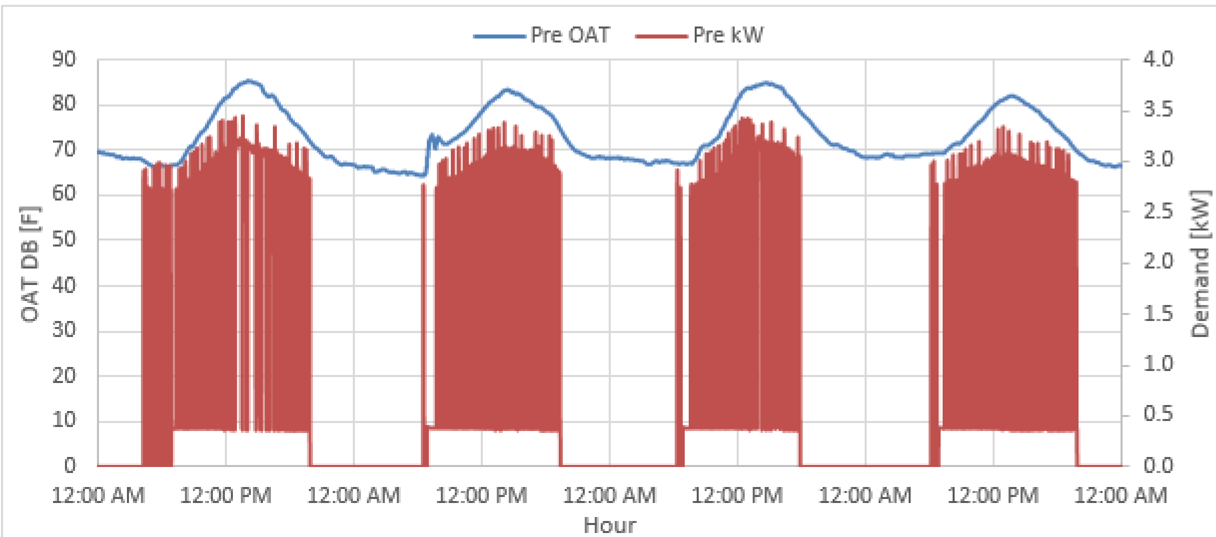
AC4

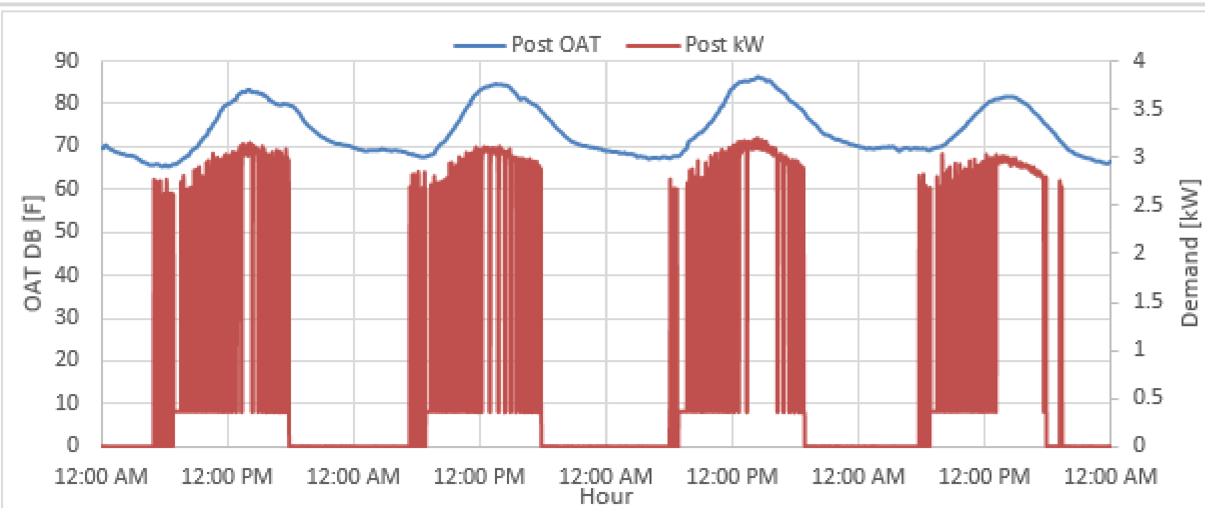
The energy consumption of this unit slightly increased after the retrofit across all temperature range. The space temperature remained the same before and after the retrofit. On the similar weather day and week comparison charts, the unit operated continuously during the afternoon while it did not before the retrofit. All of these may be an indication that the space cooling load has increased after the retrofit.


AC4 Pre kW
AC4 Post kW
Linear (AC4 Pre kW)
Linear (AC4 Post kW)
Hourly Average Demand [kW]
0
0.5
1
1.5
2
2.5
3
3.5
4
60
65
70
75
80
85
90
95
100
OAT DB [F]


AC4 Pre
AC4 Post
INDT DB [F]
70
71
72
73
74
75
76
77
78
79
80
7
8
9
10
11
12
13
14
15
16
Hour

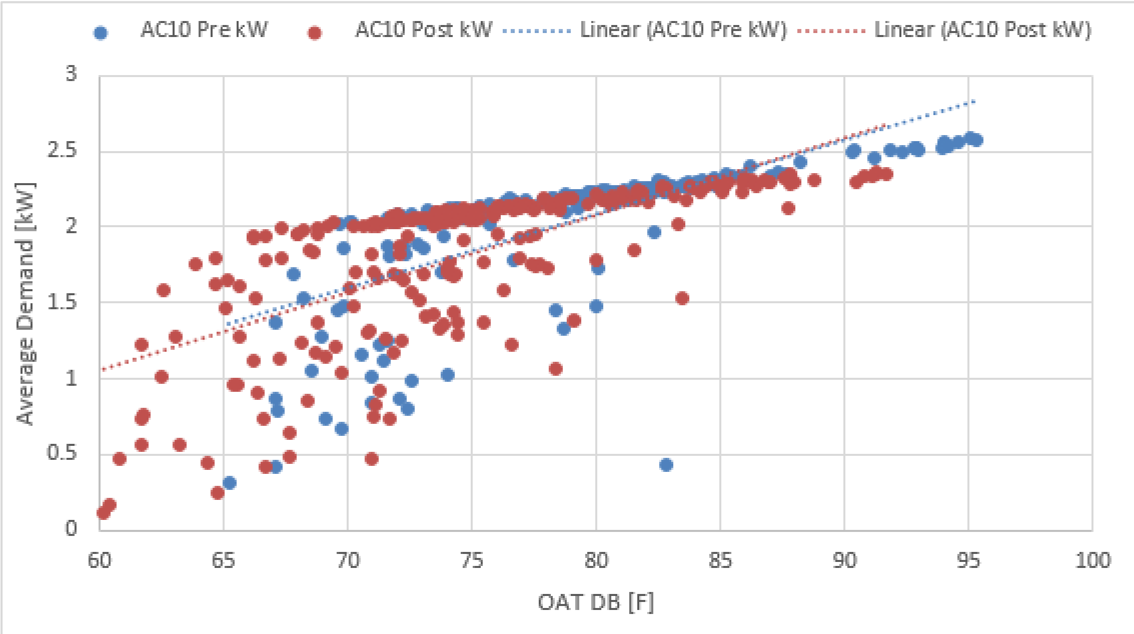

Pre OAT
Post OAT
Pre kW
Post kW
OAT DB [F]
Demand [kW]
90
80
70
60
50
40
30
20
10
0
4
3.5
3
2.5
2
1.5
1
0.5
0
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour

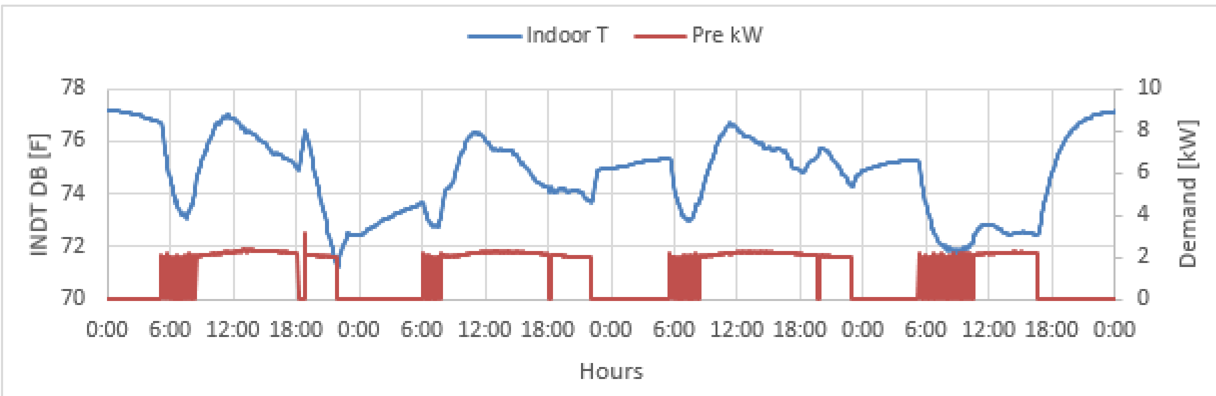

Pre OAT
Pre kW
OAT DB [F]
Demand [kW]
90
80
70
60
50
40
30
20
10
0
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
Hour

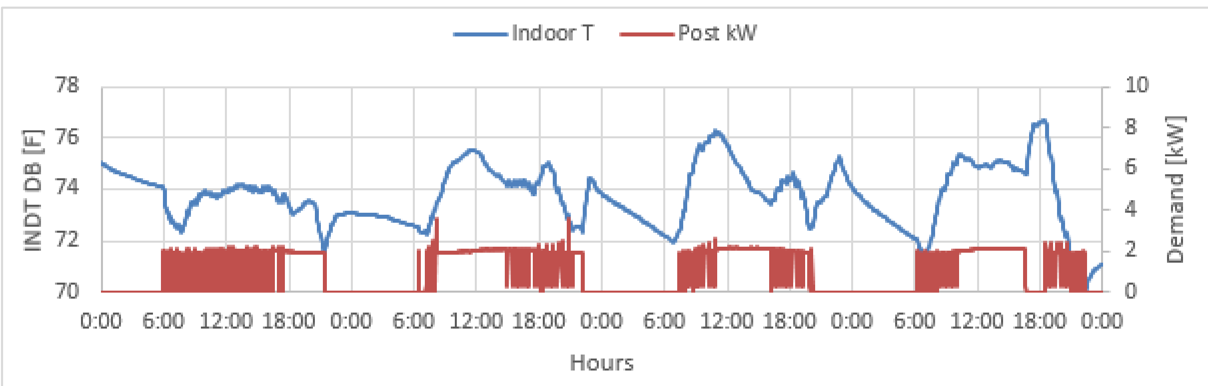

Post OAT
Post kW
OAT DB [F]
Demand [kW]
90
80
70
60
50
40
30
20
10
0
4
3.5
3
2.5
2
1.5
1
0.5
0
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
12:00 PM
12:00 AM
Hour

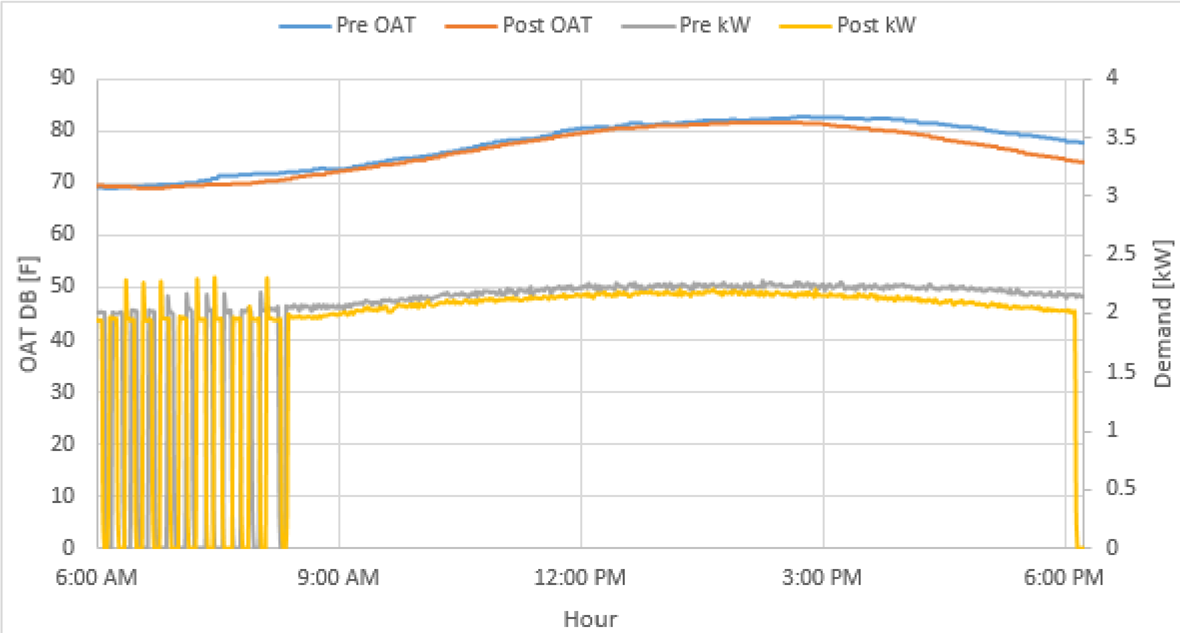
AC10

No change in energy consumption was observed for the unit AC10 serving an office. The unit was observed to be undersized for the space because the indoor temperature floated up while the compressor ran continuously. No significant change was observed for the unit's cycling operation.





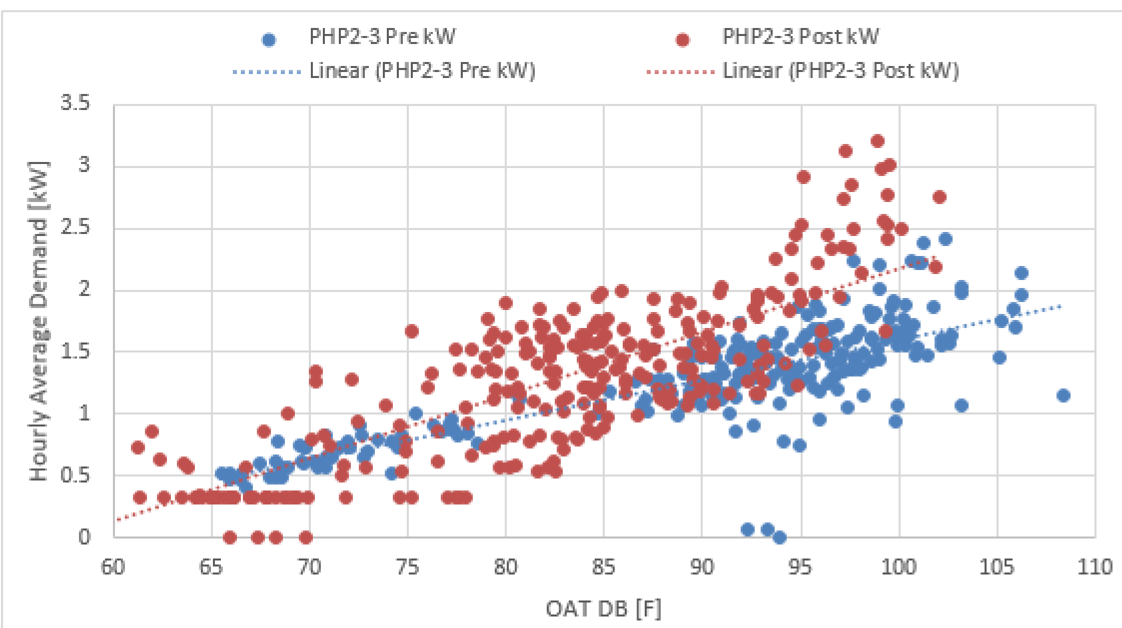


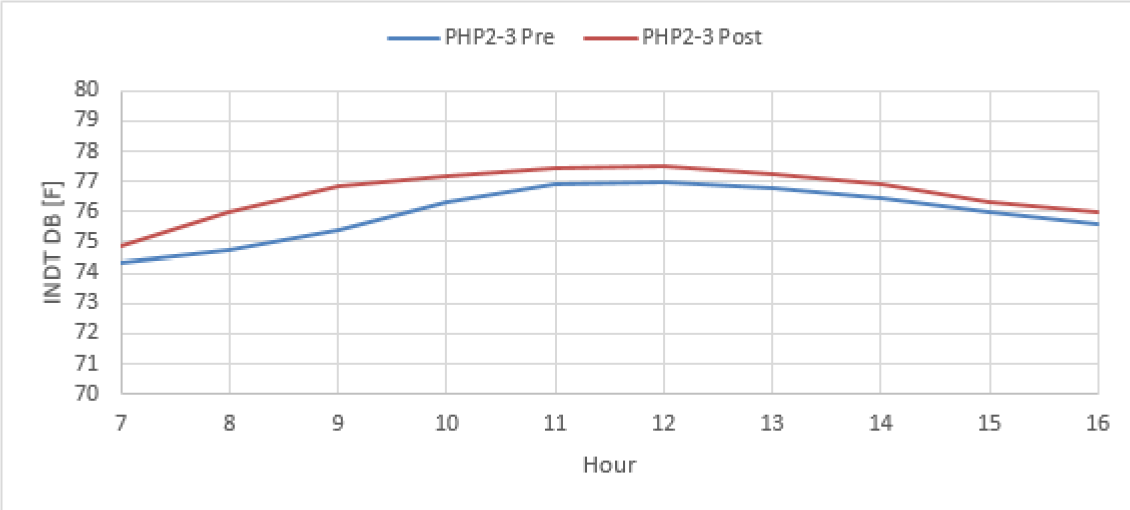


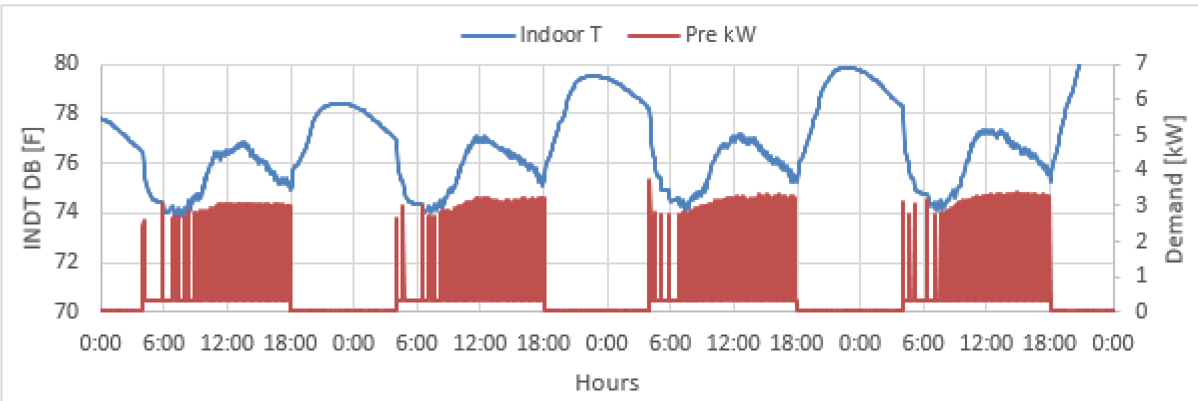
POWAY SITE

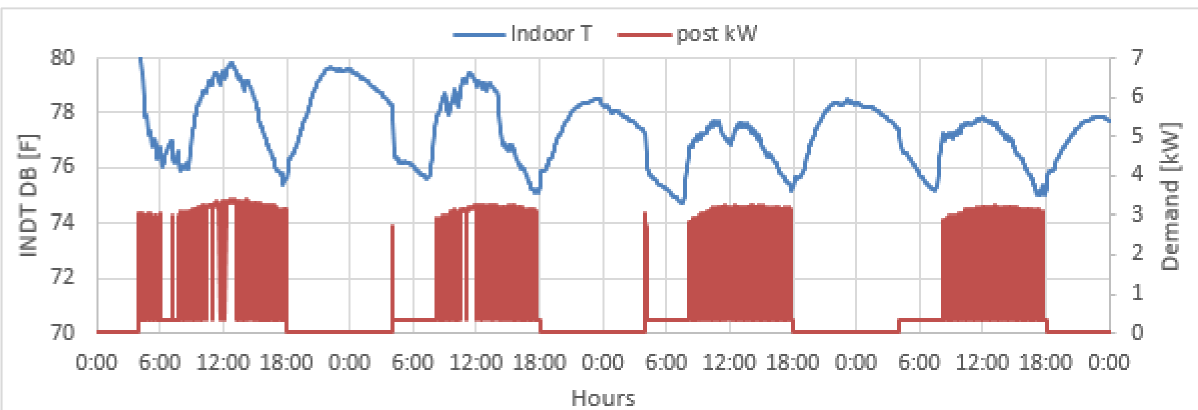
PHP2-3

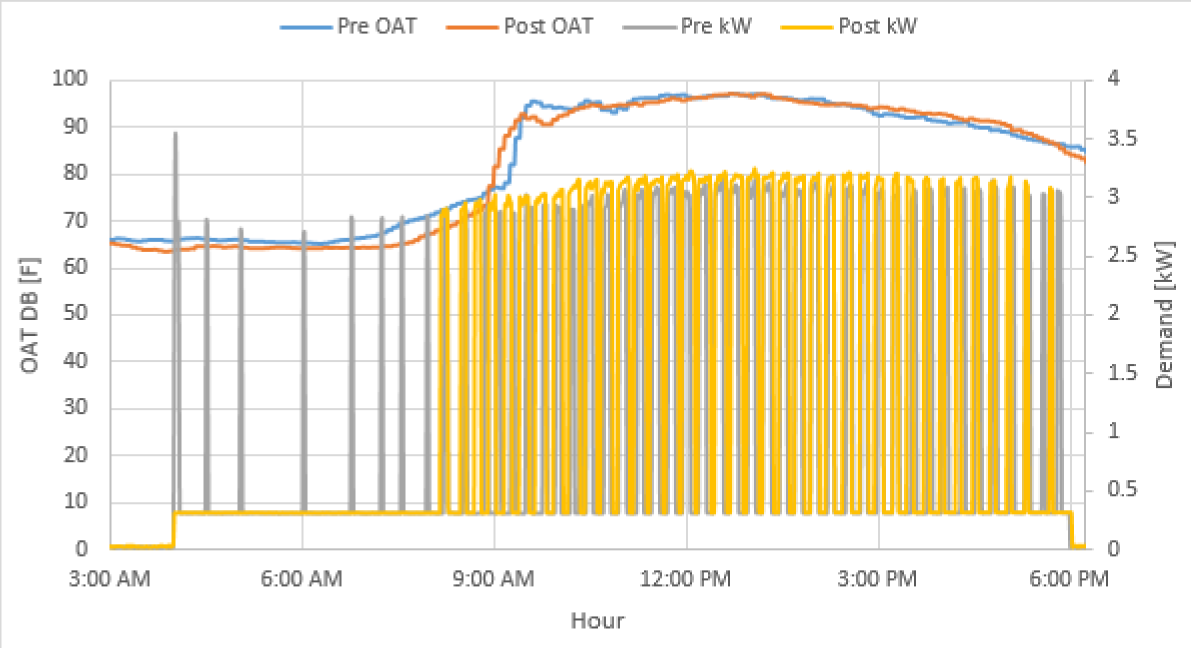
Unit PHP2-3 conditioned a conference room with large windows on the south wall. Similar to the PHP2-2 unit that was retrofitted with controller A, the space temperature increased in both periods even though compressor cycled off frequently. Again, it is possible that the logger's space temperature reading may have been different from that of thermostat due to the sun hitting the logger directly from the window. Regression analysis showed that the hourly average demand was higher during the post period.




PHP2-3 Pre
PHP2-3 Post
INDT DB [F]
80
79
78
77
76
75
74
73
72
71
70
7
8
9
10
11
12
13
14
15
16
Hour

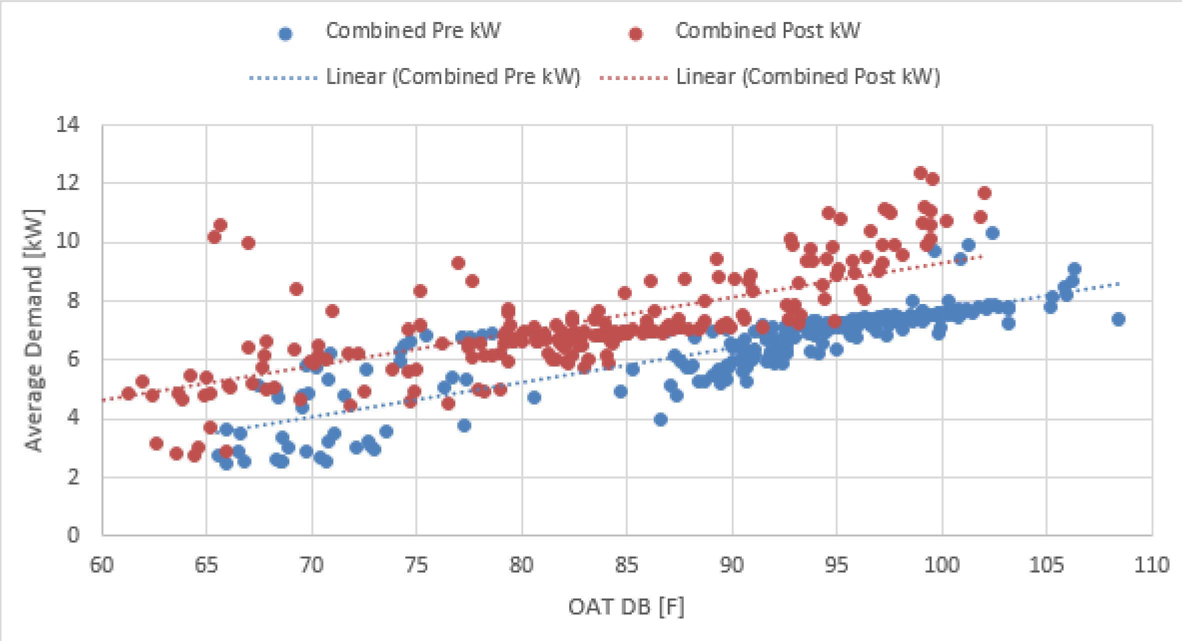

Indoor T
Pre kW
INDT DB [F]
Demand [kW]
80
78
76
74
72
70
7
6
5
4
3
2
1
0
0:00
6:00
12:00
18:00
Hours

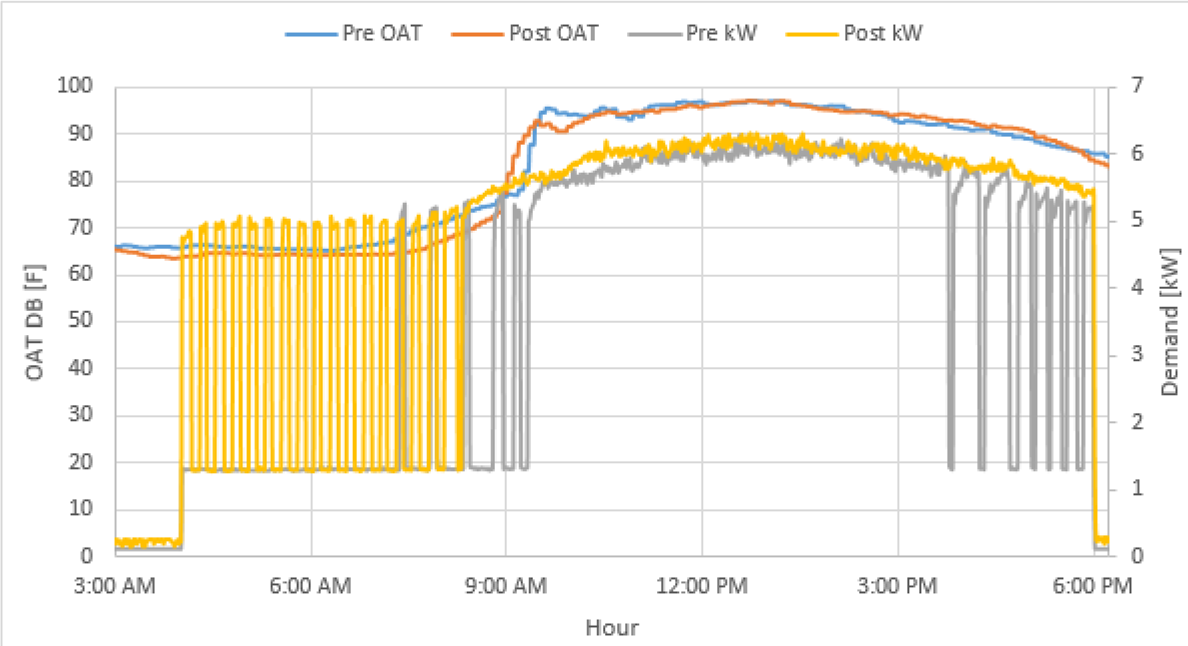

Indoor T
post kW
INDT DB [F]
Demand [kW]
80
78
76
74
72
70
7
6
5
4
3
2
1
0
0:00
6:00
12:00
18:00
Hours



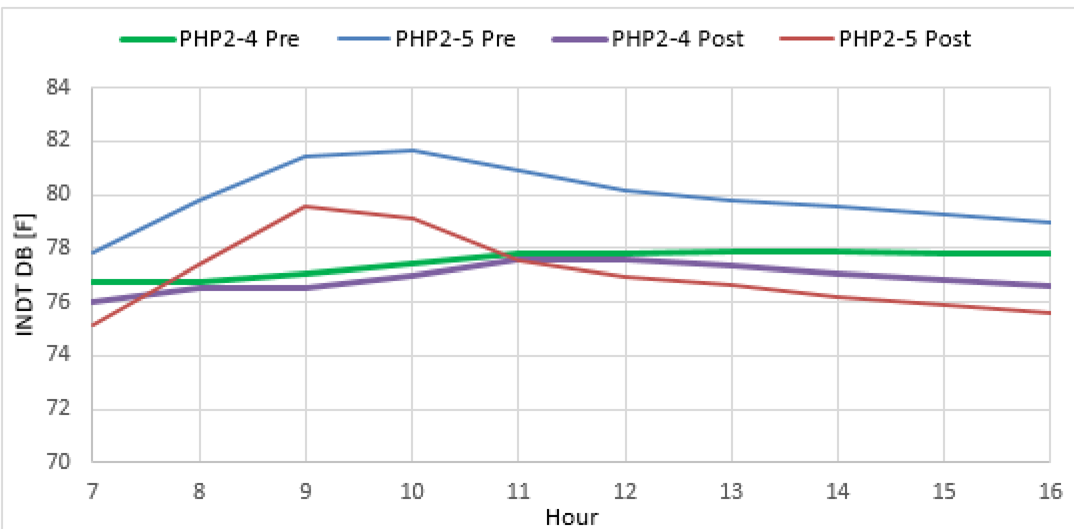
PHP2-4 & PHP2-5

Both unit PHP2-4 and PHP2-5 serve lunch/break room. Since the unit that was carrying the most of the load in the space appeared to have switched from PHP2-5 to PHP2-4 during the course of study, the analysis was performed by combining the energy consumptions of the two units. The regression analysis in Figure showed that the average hourly energy consumption of the two units increased after the retrofit.



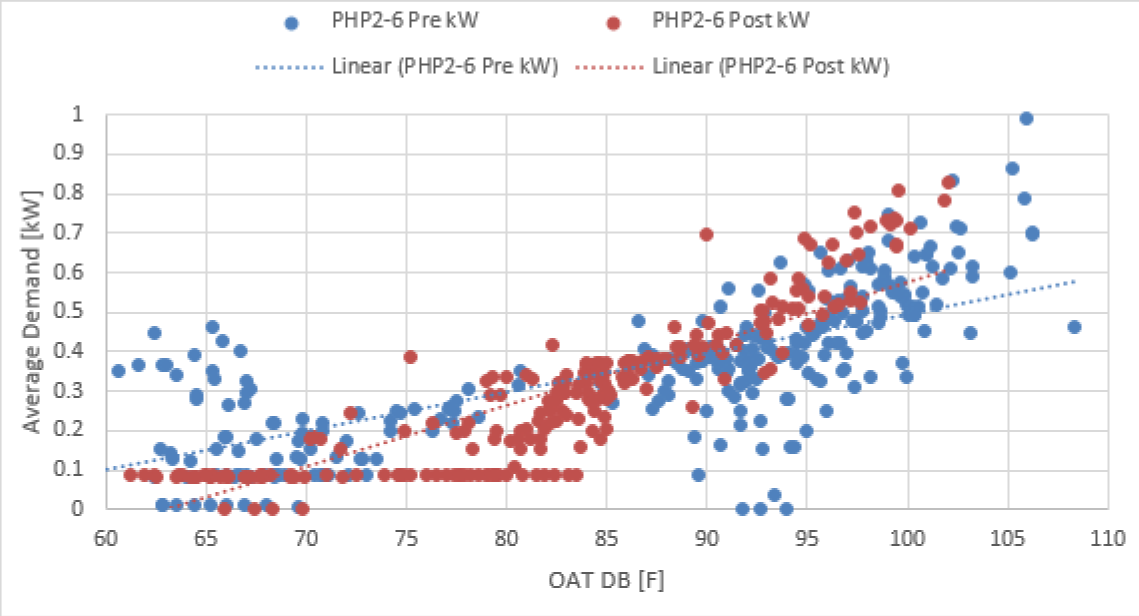


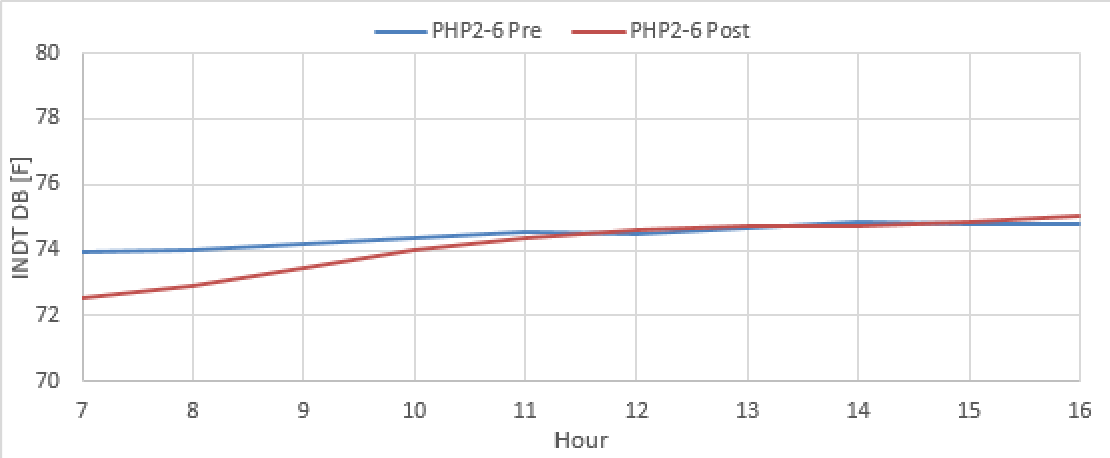
The increase in energy consumption may be due to the location of thermostats, which are located in the opposite ends of the room. Figure below shows the average indoor temperatures recorded by the two thermostats. Although indoor temperatures recorded by PHP2-4 remained relatively the same before and after the retrofit, the space temperature recorded by PHP2-5 decreased significantly, approximately by 2.5 degrees.

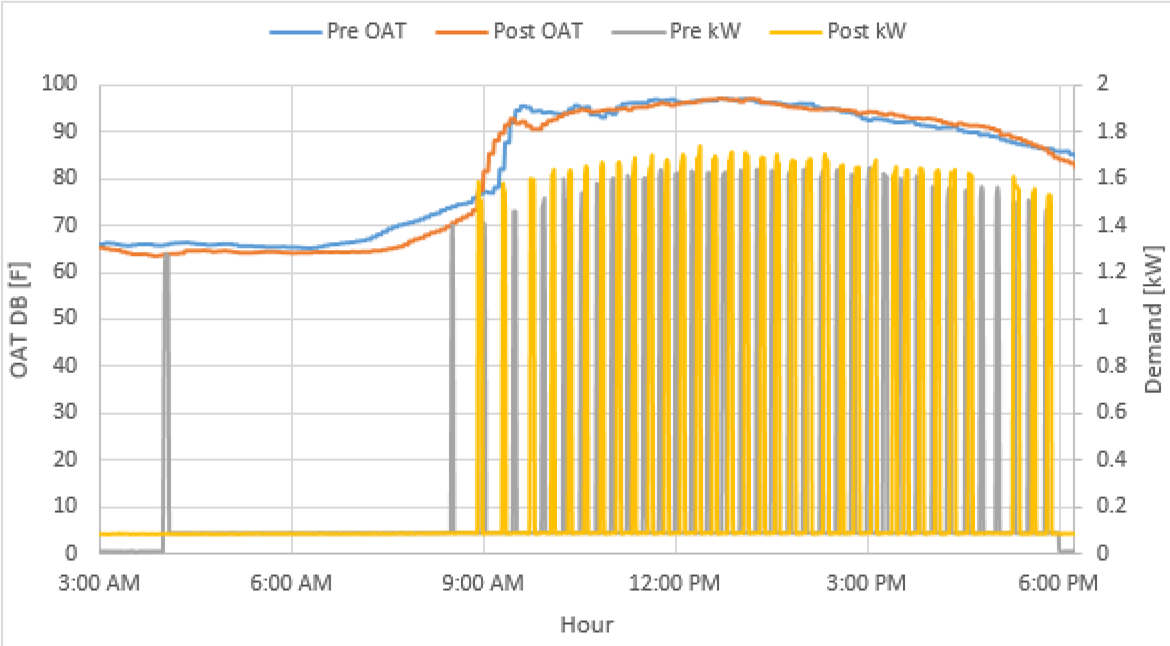


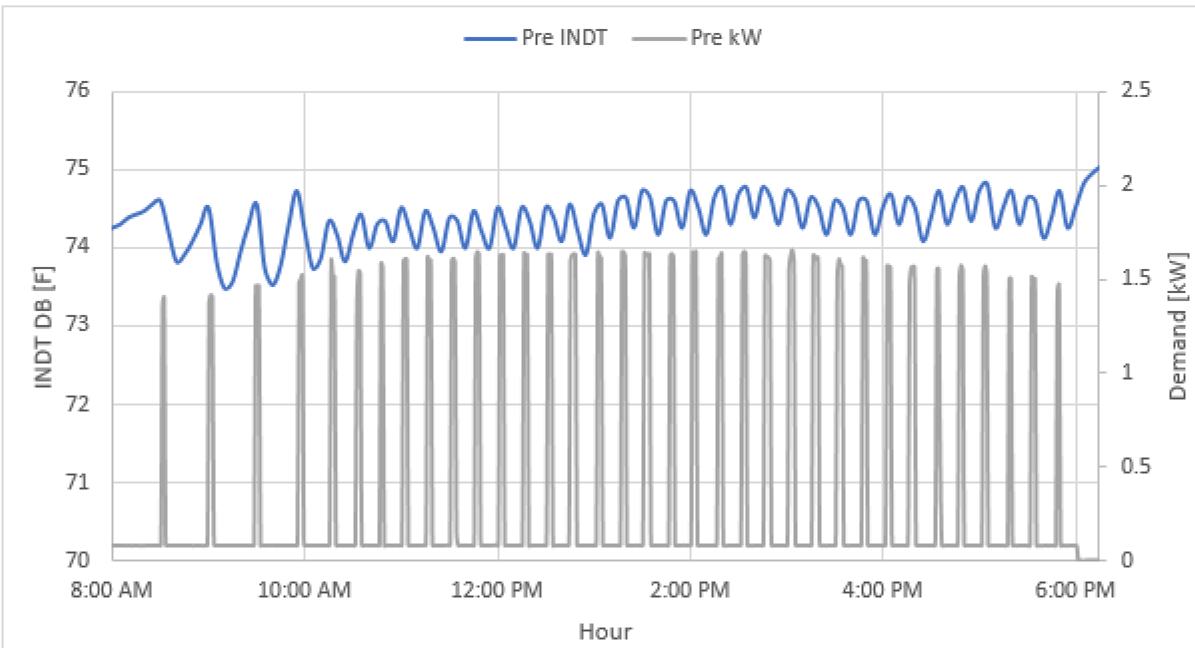
PHP2-6

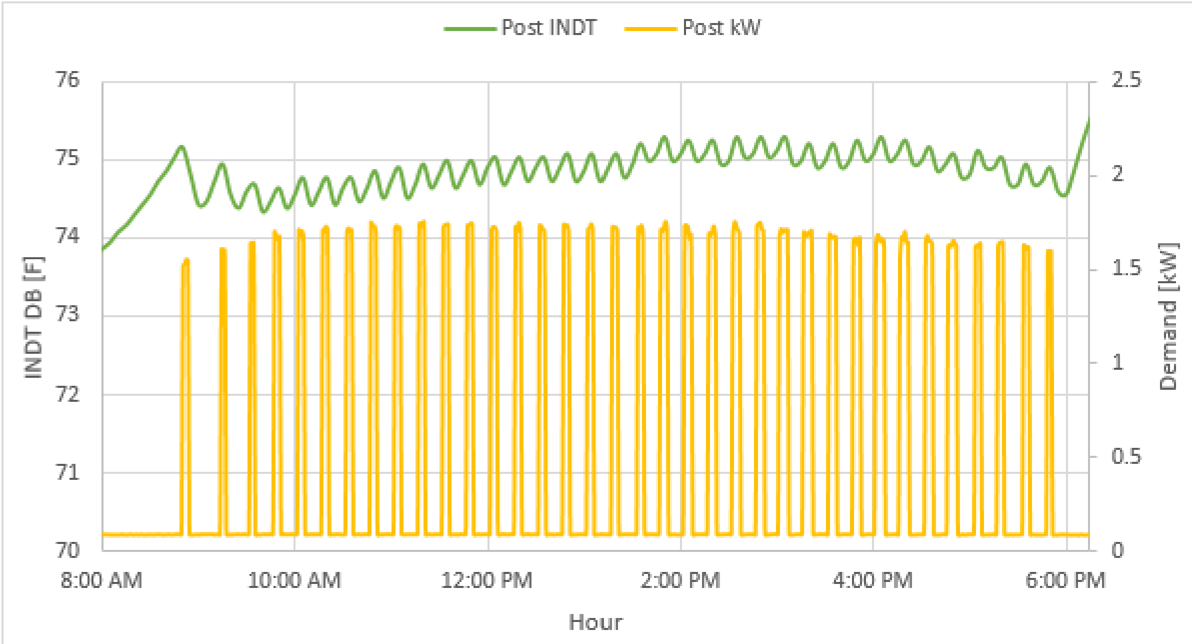
Unit PHP2-6 served a media room with equipment that is typically unoccupied. The average hourly demand data showed an increase in consumption at a higher temperature range but the difference was small. The indoor temperatures were kept relatively constant before and after the retrofit and no significant change was observed for unit's cycling behavior.


PHP2-6 Pre kW
PHP2-6 Post kW
Linear (PHP2-6 Pre kW)
Linear (PHP2-6 Post kW)
Average Demand [kW]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
60
65
70
75
80
85
90
95
100
105
110
OAT DB [F]


PHP2-6 Pre
PHP2-6 Post
INDT DB [F]
80
78
76
74
72
70
7
8
9
10
11
12
13
14
15
16
Hour

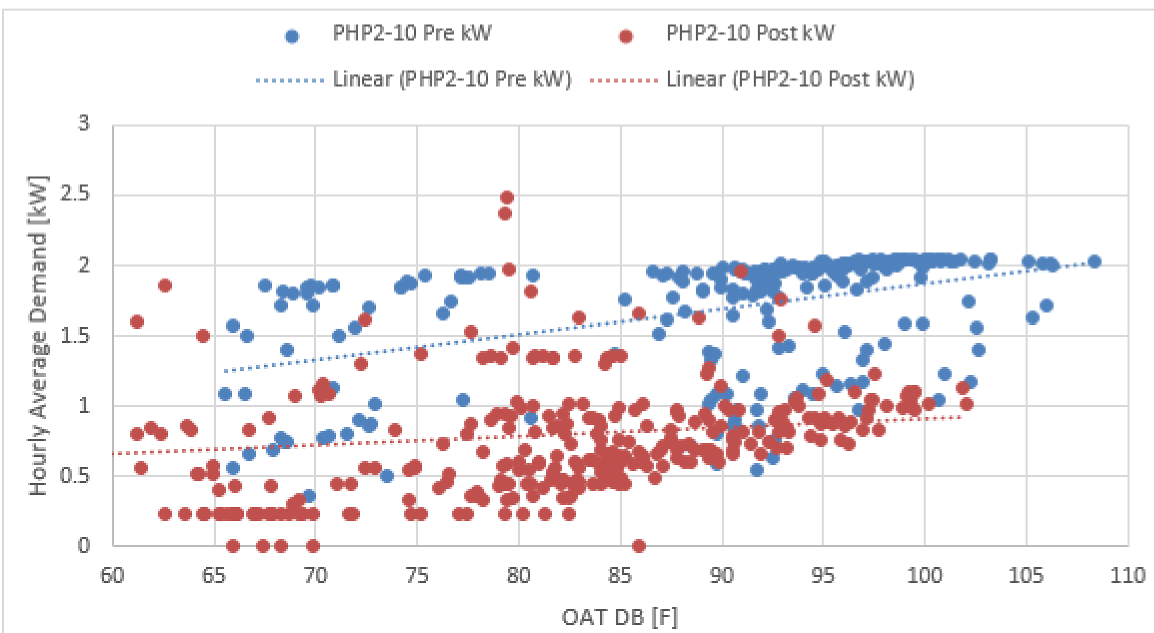

Pre OAT
Post OAT
Pre kW
Post kW
OAT DB [F]
100
90
80
70
60
50
40
30
20
10
0
Demand [kW]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
3:00 AM
6:00 AM
9:00 AM
12:00 PM
3:00 PM
6:00 PM
Hour

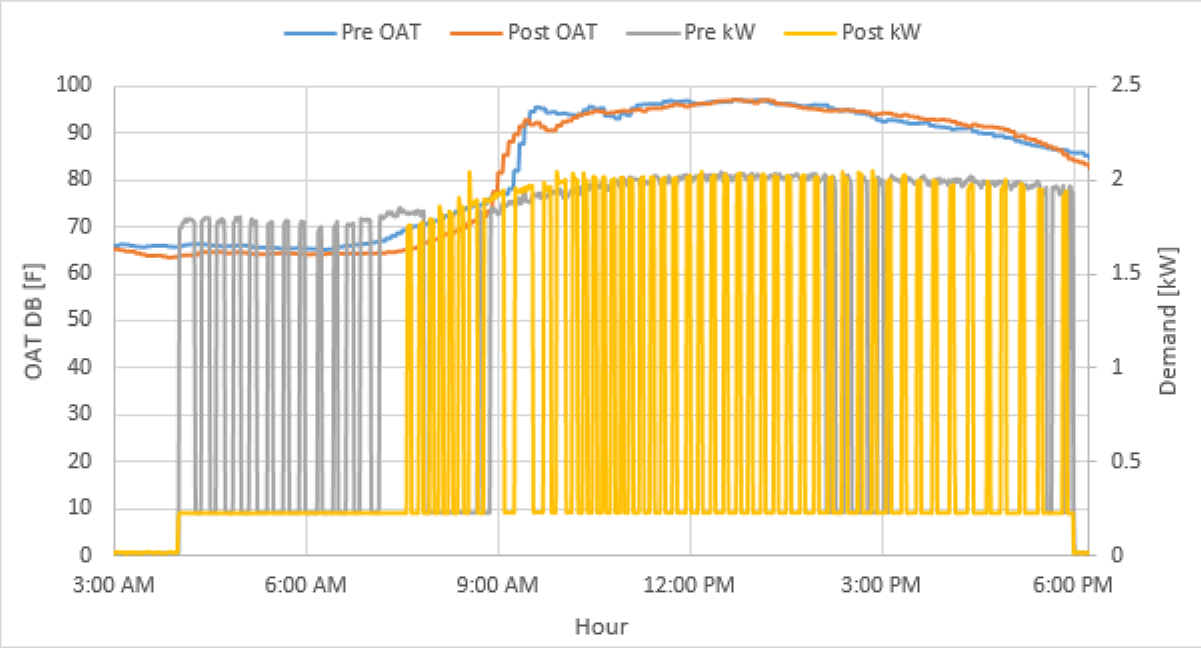

Pre INDT
Pre kW
INDT DB [F]
76
75
74
73
72
71
70
Demand [kW]
2.5
2
1.5
1
0.5
0
8:00 AM
10:00 AM
12:00 PM
2:00 PM
4:00 PM
6:00 PM
Hour



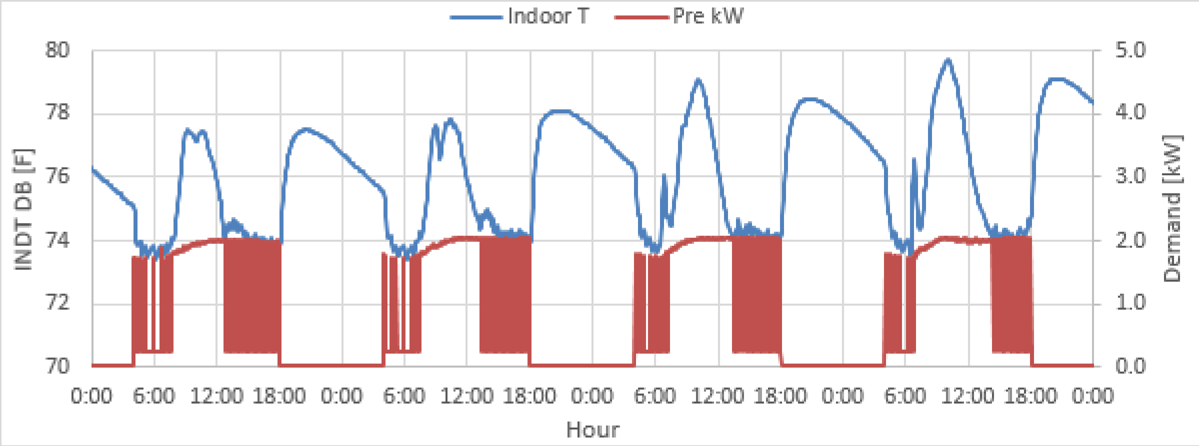
PHP2-10

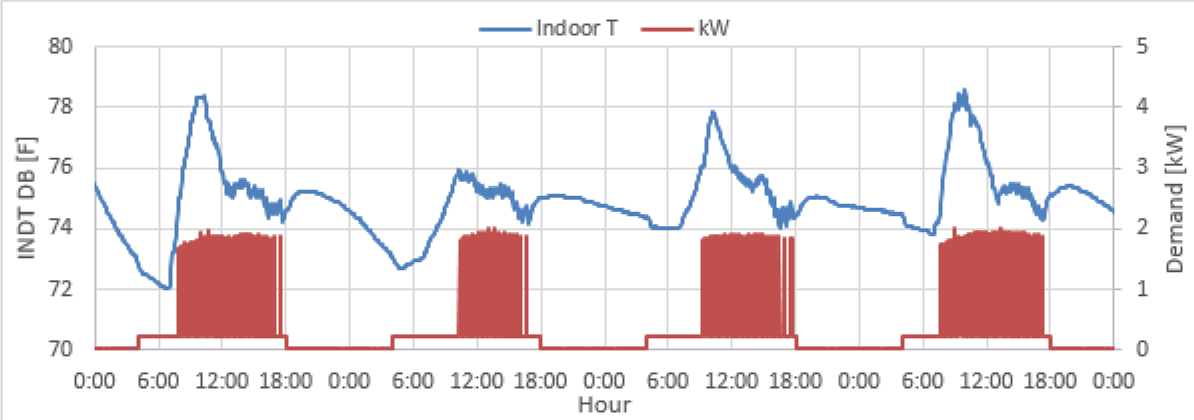
As shown in Figure below, decrease in energy consumption was observed for unit PHP2-10 serving an office with east facing windows. Savings observed are mainly due to more frequent cycling that occurred after the technology implementation. However, the closer look at the indoor temperature and the unit operation show disconnect between the space temperature and the unit operation.

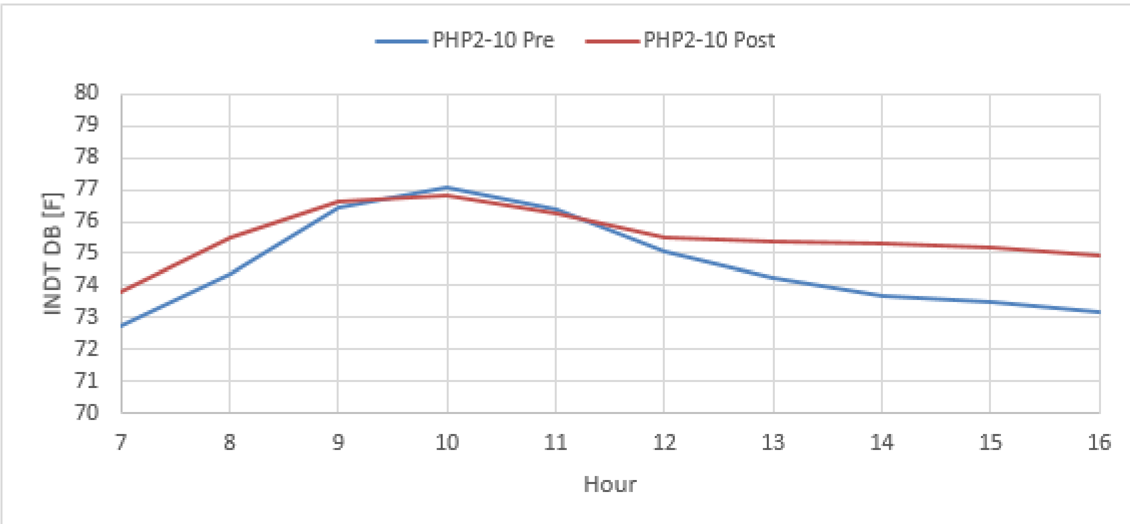




Prior to the technology implementation, the indoor temperature floated up while the compressor ran continuously, which is expected, because it indicates that the unit was undersized for the space. After the installation, however, the unit cycled even when the space temperature increased during the day, before noon. In fact, the average hourly indoor temperature shows that the space temperature was slightly higher in both morning and afternoon after the technology implementation.







The thermostat for this unit was located on the west wall, facing the east windows. One possible explanation for the space temperature increase observed at the thermostat (usually before noon) would be that the sun rays were directly hitting the thermostat, heating up the fixture. Since the installed technology used additional temperature sensor in the return duct to control compressor cycling, it is possible that the space temperature was actually lower than the temperature sensed at the thermostat and that the compressor was cycled properly after the retrofit. Since only one data logger was placed in the room and because the logger was placed directly above the existing thermostat, we can't confirm if this theory proves.