Advanced Rooftop HVAC Unit Controls Pilot

Conservation Applied Research & Development (CARD)
FINAL REPORT

Prepared for: Minnesota Department of Commerce, Division of Energy Resources

Prepared by: Center for Energy and Environment and PECI

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Prepared by:

Center for Energy and Environment
212 3rd Avenue North, Suite 560
Minneapolis, MN 55401
612-335-5858
www.mncee.org

Rich Szydlowski (rszydlowski@mncee.org 612-335-5862)
Mark Hancock (mhancock@mncee.org 612-335-5861)
Alex Haynor (ahaynor@mncee.org 612-244-2415)

PECI
100 SW Main Street, Suite 1500
Portland, OR 97204
503-248-4636
www.peci.org

Kristine Falletta (kfalletta@peci.org 503-575-4163)
Benjamin Lipscomb (blipscomb@peci.org 503-522-7140)
Alexander Reed (areed@peci.org 503-248-4636)

Contract Number: 34452

Prepared for Minnesota Department of Commerce, Division of Energy Resources

Mike Rothman, Commissioner, Department of Commerce

Bill Grant, Deputy Commissioner, Department of Commerce, Division of Energy Resources

Mary Sue Lobenstein, Program Administrator
651-539-1872
marysue.lobenstein@state.mn.us

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DISCLAIMER

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1) EXECUTIVE SUMMARY

A number of new products on the market claim to deliver energy savings to existing roof top air handling systems. The Center for Energy and Environment wanted to field test these products and their manufacturer's claims of savings in a climate that is not predominately cooling, such as Minnesota's. The roof top unit (RTU) market is estimated at 46 percent of all commercial spaces in Minnesota (EIA, 2003), which includes offices, manufacturing, warehousing, and other box-type properties. Despite RTUs market share, very few options can improve their efficiency. The construction industry uses RTUs to lessen initial development costs without considering the long-term operational costs for the owner or tenant. These new energy-saving products could improve the inherently low performance of standard roof top systems and achieve significant savings for the building operator/owner or tenant.

The research team proposed to study the potential of advance control optimizers to save money in Minnesota's climate. This research was funded by the Minnesota Department of Commerce, Division of Energy Resources, Conservation and Applied Research Development Grant program. This pilot evaluated three optimizers which demonstrated sufficient product maturity and market readiness to be tested in a pilot research project: Catalyst, Digi-RTU, and Premium Ventilation.

Previous studies had documented the energy consumption characteristics of buildings with RTUs and then installed the optimization packages to document resulting savings. However, this type of study took place over a two-year time span that makes it difficult to compare pre-and post-installation energy use. This methodology could not account for factors such as change in business, addition or subtraction of workers, and the typical up and down of economic cycles. The research team selected a flip/flop testing protocol. This test design allowed the pilot to capture performance data in a single year. It also ensured that changes within the building would be accounted for when evaluating the performance of both optimized and basic operation. The research team installed the necessary hardware to allow the RTUs to operate in both basic and optimized or advanced modes of operation. The data acquisition system automatically switched between modes weekly to capture nearly identical activities within the building and weather conditions outside the building.

The study targeted the most commonly found RTU size ranges with a single thermostat control per unit. It collected performance data of 62 RTUs across six different sites. The RTUs were fitted with one of three optimization packages, and wherever possible all the RTUs at a site received the optimization. Some sites modified their RTUs between the site selection and instrumentation phases, resulting in RTUs which could not be fitted with optimization packages. While this was not planned the research team elected to continue with the use of the sites. The RTUs that didn't receive optimization at these sites were monitored for control purposes and studied to document their operation in comparison with the other RTUs which switched between advance control and basic control. The data collection period spanned 13 months, including both summer and winter time periods. The pilot collected additional data at some sites, and limited data at one site due to tenant relocation.

The study documented issues with operation of the advanced controls. A number of these issues resulted from of the installation of the advanced controls, and others resulted from unexpected operational problems during the monitoring period. The research team resolved some issues by modifying the software setpoints, but was unable to resolve other more severe issues.

Performance issues were limited to the Catalyst and Digi-RTU systems. The Catalyst's problems stemmed from the startup commissioning process's failure to fully account for the interactions between the RTUs integral safeties and the settings on the Catalyst's default setpoints. Solutions were found to solve these problems with the assistance of both the factory representatives and the installing technicians.

The Digi-RTU had two major issues that were not resolved during our testing period: many single phase supply fan motors failed due to variable frequency drive (VFD) operation, and the Digi-RTU controls were not able to operate during extreme outside air temperatures. The factory assured the research team that the Digi-RTU controllers would operate single phase supply fan motors without issues as they had tested them prior to our work. The extreme weather issue was first documented by this research study and was previously unknown to the manufactures.

The pilot processed performance data down to daily consumption values for both electric and gas. Consumption was plotted against average outside air temperature to develop a model of energy consumption for both the occupied and unoccupied periods for each mode of operation. Additional parameters were captured by the monitoring system to evaluate space temperature and relative humidity along with indoor air quality as indicated by Carbon Dioxide (CO_2) readings. These parameters were collected to assure that conditions didn't change between the advanced control mode and basic mode of operation.

The results of the data analysis showed that all the optimization packages saved energy. All advanced controls packages produced statistically significant electric energy savings at the 90 percent confidence level. As a percentage of baseline RTU energy use, the Catalyst and Digi-RTU controls both achieved approximately 30 percent electric energy savings, and the Premium Ventilation achieved approximately 15 percent electric energy savings. Gas energy savings were significantly more variable than electric energy savings. Catalyst and Digi-RTU resulted in statistically significant negative gas energy savings. The Premium Ventilation and control units also resulted in negative gas savings estimates, but the results are not statistically significant at the 90 percent confidence level. Savings for both the electric and gas by technology are displayed in Figure 1. Electric Energy Savings by Technology and Figure 2. Each optimization package is identified by name and the category of "none" displays the RTU's that didn't receive optimization or the controls units.

Figure 1. Electric Energy Savings by Technology

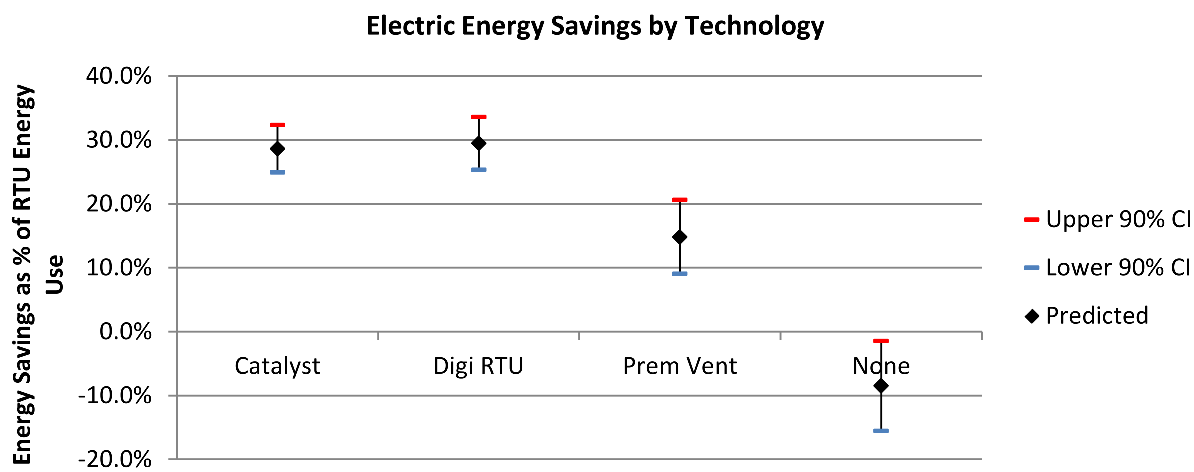
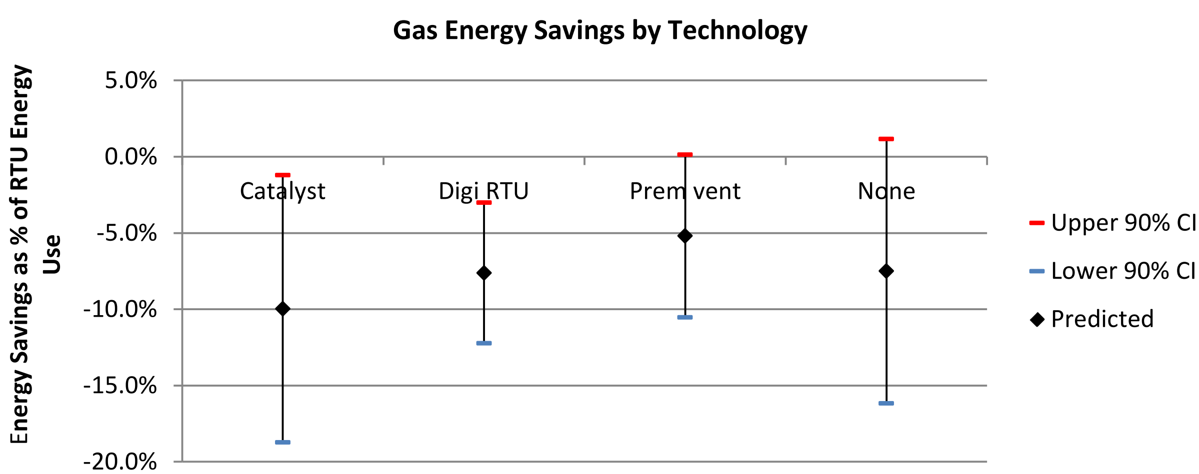


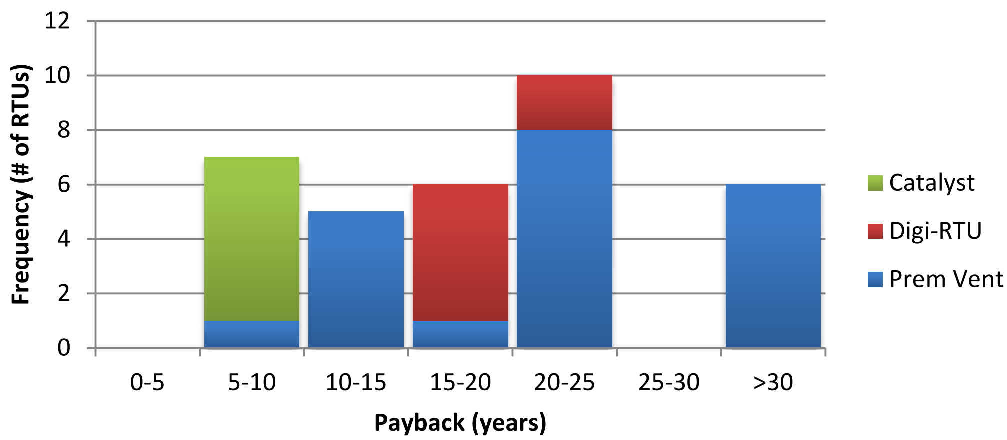
Figure 2. Gas Energy Savings by Technology



The analysis captured typical installation costs and used them to generate a payback for each of the advanced control packages. Costs for hardware can be estimated with a high degree of confidence. The costs for the labor and unknown installation variances were much more difficult to estimate. To standardize the analysis, a set of standard buildings were generated and each of the manufactures supplied costs for implementation of their control packages on these buildings with the assumption of average level of effort to install the advanced controls. These costs, along with energy savings, were used to generate payback numbers for each advanced control type. These paybacks are plotted in Figure 3.

Under the conditions of the test, none of the technologies achieved energy savings that could be considered cost-effective using a simple payback of five years as the upper threshold. A number of factors affected this result, primarily size. The RTUs in the study averaged 7.8 tons per unit, which is somewhat smaller than desired for the installation of control strategies like the ones studied here. The advanced controls packages that require significant hardware which resulted in higher costs, such as the Catalyst and Digi-RTU, would achieve much shorter paybacks on larger RTUs. The Premium Ventilation control had lower hardware costs but significantly higher and variable labor costs for installation. This variability in installed costs for the Premium Ventilation caused the paybacks to span from a respectable range of 5 to 10 years up to paybacks that exceed 30 years

Figure 3. RTU Frequency by Payback Range and Technology



While the cost-effectiveness doesn't suggest that the advanced control packages would be recommended for consideration for a Conservation Improvement Program (CIP) offering, if the program were structured to target the larger RTUs, these control packages could provide energy reductions for the client and documented energy savings for the utility. The program would have to manage the factors that affect the cost effectiveness for the potential sites where these systems would be installed, which includes: RTU size, occupant density, and operation schedule. Additionally, the program should not expend retrofit funds on an older RTU that has limited life left.

The research team successfully documented the parameters necessary to evaluate a potential CIP program focused on RTU optimization, an important result since the current market for optimization is developing at a speed requiring annual evaluations of the latest offerings and technologies. This rapid market movement is the result of lower and lower technology costs coupled with advances in wireless communication that make optimization more cost-effective for building owners willing to implement the technology.

Advanced RTU controls offer an opportunity to greatly improve the energy efficiency of the tens of thousands of existing RTUs in Minnesota. This pilot and other studies have shown that the controls strategies are technically sound and have field tested energy savings potential. However, the existing products early development cycle and associated costs limit their ability to quickly achieve large market penetration. A CIP program that offers market development services, contractor support services and rebates could accelerate the market acceptance of this new energy efficiency product. The CIP program design would be necessarily sophisticated, not just a simple prescriptive rebate. Such a CIP program has the potential to improve the energy efficiency of most of Minnesota's small to medium businesses which rely heavily on RTUs.

2) INTRODUCTION

The goal of this pilot project was to evaluate the cost effectiveness of three advanced Rooftop HVAC Unit (RTU) control strategies. Energy reduction potential and the cost-effectiveness of each control package was determined to inform utilities on the appropriateness for a large scale delivery offering by a Conservation Improvement Program (CIP).

3) BACKGROUND

RTUs serve 46 percent of commercial floor space (EIA, 2003), making them one of the most commonly encountered HVAC systems in this sector. The reasons for this penetration are low initial costs, integration of heating and cooling in a single unit, reliability, and the availability of trained installers and service technicians. These factors, coupled with standard offering for size ranges, make the selection of an RTU a "plug and play" offering for the developer or designer of these buildings. Once the RTU is installed, there are few cost effective options to improve its energy efficiency. Typically, the only option is to install a new RTU with a high SEER value, which is expensive and has a long payback. Additionally, there are limited options for high-efficiency models from the manufacturer. Furthermore, the only time that high-efficiency replacements are considered is when a pre-planned replacement is coordinated with the removal of an existing unit near the end of its useful life, which is atypical for this market. These factors make a retrofit with new advanced technologies an attractive option to existing building owners.

Rooftop advanced control optimization has become the only option to improve the energy efficiency of the existing rooftop market. There are many versions of optimization packages employing a variety of technologies to reduce the energy consumption of the rooftop unit without sacrificing occupant comfort.

4) METHODOLOGY

4.1) Summary of Optimization Packages

Table 1. Summary of Advanced Control Optimizers

Advanced Control	Primary means of energy reduction	Hardware to achieve reduction	Features
Catalyst Controller	Supply fan speed reduction, integrated economizer	VFD on supply fan	DCV, Web Interface, Fault Detection, Demand response
Digi-RTU Optimizer	Refrigeration compressor and supply fan speed modulation	Single VFD on compressor and supply fan	DCV, Fault Detection
Premium Ventilation	Intelligent setpoint modification, economizer control	Advanced programmable controller with addition sensors	DCV, Optimal Start, Occupancy-based setpoints

The research team selected three different optimization packages for evaluation in this pilot research project. A high-level summary of the each of the optimization package along with the theory of operation is given in Appendix A; along with installation experience, issues with operation, and installation costs for each package. The theory of operation is by no means an exhaustive detail into the operation of each system, but rather a high-level description of each optimization package and details about the options for each package. Table 1 gives a summary of the three advanced control packages.

4.2) Large-Scale Installation

The study captured typical installation costs and used them to generate a payback for each of the advanced control packages. Costs for hardware can be estimated with a high degree of confidence. The costs for the labor and unknown installation variances were much more difficult to estimate. To standardize the analysis, a set of standard buildings with standard RTU's were generated and each manufacturer supplied costs for implementation of their control packages on these buildings, assuming an average level of effort to install the advanced controls. The standard buildings were not intended to represent a category of business type but simply a size of building that would require the number of RTU's in each of the size categories (small, medium, and large). These costs along with savings were used to generate payback numbers for each advanced control type.

The Tables below summarize the details of the site. Cooling capacities were set for each RTU primarily because most of the advanced control focused on the cooling energy and the cooling capacity dictated the size and therefore the cost of the upgrade.

Table 2. Small Site (3 RTUs)

RTU ID	Cooling capacity (ton)
RTU-1	7.5 ton
RTU-2	10 ton
RTU-3	12 ton

Table 3. Standard Site (10 RTUs)

RTU ID	Cooling capacity (ton)	RTU ID	Cooling capacity (ton)
RTU-1	5	**RTU-6**	10
RTU-2	5	**RTU-7**	10
RTU-3	7.5	**RTU-8**	12
RTU-4	7.5	**RTU-9**	12
RTU-5	10	**RTU-10**	15

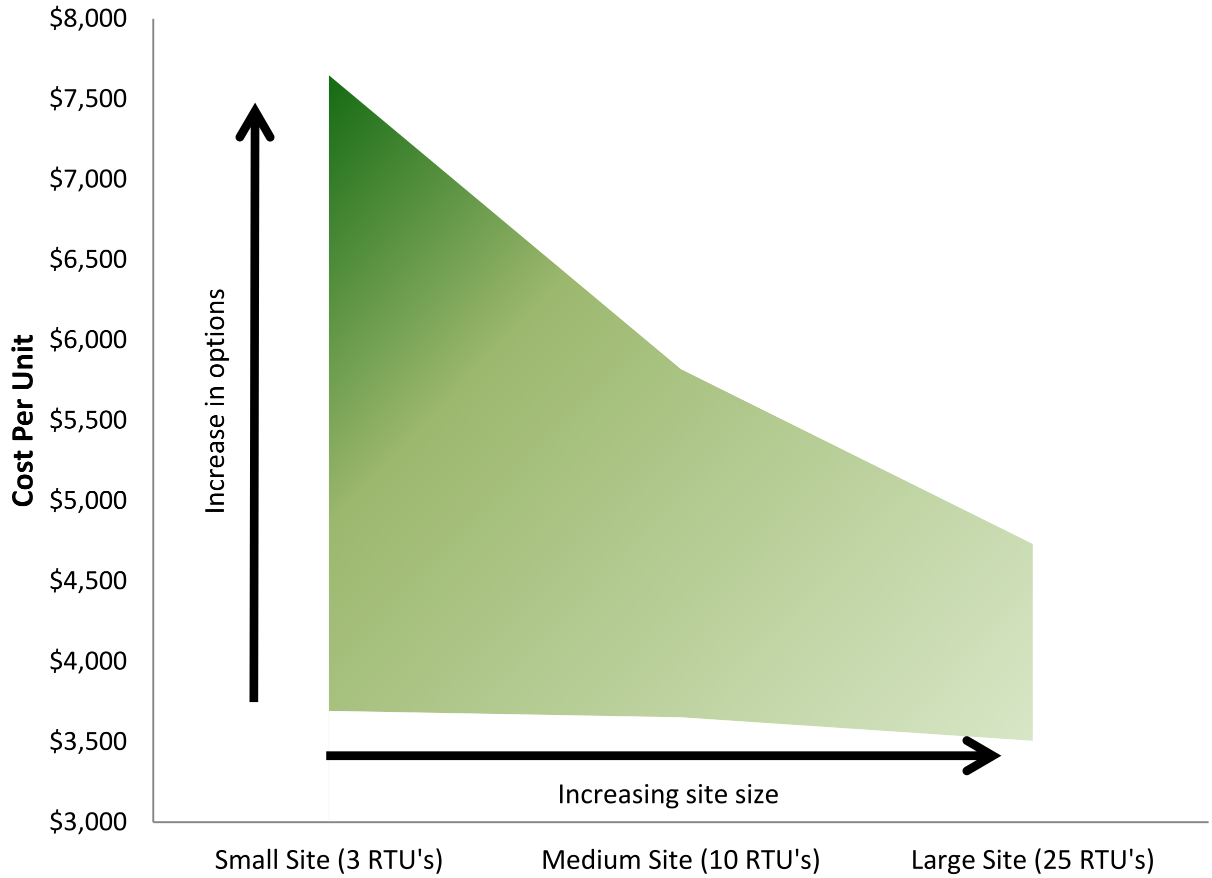
Table 4. Large Site (25 RTUs)

RTU ID	Cooling capacity (ton)	RTU ID	Cooling capacity	RTU ID	Cooling capacity (ton)
RTU-1	5	RTU-10	10	RTU-19	12
RTU-2	5	RTU-11	10	RTU-20	12
RTU-3	5	RTU-12	10	RTU-21	12
RTU-4	5	RTU-13	10	RTU-22	12
RTU-5	7.5	RTU-14	10	RTU-23	15
RTU-6	7.5	RTU-15	10	RTU-24	15
RTU-7	7.5	RTU-16	12	RTU-25	15
RTU-8	7.5	RTU-17	12		
RTU-9	7.5	RTU-18	12		

For this large scale simulation activity, no installation data could be collected for the Premium Ventilation package because there wasn't local support to install the optimizer so cost data could not be estimated.

Below is a visual representation of data from the Catalyst manufacturer. Because the Catalyst offers a wide variety of options, it was determined that to best represent this suite, all available options would be referenced in this analysis. From Figure 4, there are six different option levels for the Catalyst, ranging from the simple standalone to the fully integrated building automation version with web access and live data. Figure 4 represents a range of costs for the installation of the Catalyst controller. As a site installs more, the cost per unit decreases to a point where the more feature-orientated models approach the cost of the more basic featured models.

Figure 4. Catalyst Costs by Size of Site



By comparison the typical installation costs for the Digi-RTU were quoted on a per ton basis. Table 5 presents the costs supplied by the manufacturer for the three standard sites.

Table 5. Digi-RTU Installation Costs

Site Size	Cooling Capacity (tons)	Total Cost	Cost per ton
Small (3 units)	29.5	$15,782	$535
Standard (10 units)	94	$47,447	$505
Large (25 units)	247	$122,024	$495

The values supplied by the manufactures and the actual costs for the Premium Ventilation installations were used as the basis for the cost-effectiveness analysis.

4.3) Monitoring Equipment

The Advanced Rooftop controls research project equipped 60 units with extensive monitoring equipment packages and collected data in five-minute intervals on a daily basis. The data collection was an automated process performed remotely with a cellular modem connected to a server.

Two types of packages were deployed on the units: base stations and satellites. There were four base stations and 56 satellites between the six sites. The base station acted as a communication hub for all of the surrounding loggers. The satellites talked to the base station, which collected the data and downloaded the previous day's data every night to the central server. The monitoring system also provided the ability to switch between the advanced controls mode and the basic control mode.

4.3.1) Equipment

All of the logging equipment for each RTU was enclosed in a fiberglass enclosure fastened to the side of the unit. Each package contained a data logger from Campbell Scientific, the CR800 for the base station and the CR206x for the satellite. The CR800s were equipped with cellular modems for communication back to the data servers and spread spectrum radios for communication with the satellites, while the CR206xs had integral spread spectrum radios for communication. All loggers were powered by some connection to main power, and had a 12VDC battery backup in the event of a power loss.

All of the packages included additional equipment for monitoring, including temperature sensors, watt transducers, current transformers, and various relays. Table 6 provides the detail of the parameters collected on each RTU and the device used to capture the parameter.

Table 6. Measured Parameters

Parameter	Units	Device
Total Unit Energy	Accumulated kWh in 5 min interval	Watt Transducer
System Runtime	Time On	Watt Transducer
System Event	Number of events	Watt Transducer
Gas Valve Stage 1 Runtime	Time On	24 VAC Relay
Gas Valve Stage 1 Event	Number of events	24 VAC Relay
Gas Valve Stage 2 Runtime	Time On	24 VAC Relay
Gas Valve Stage 2 Event	Number of events	24 VAC Relay
Return Air Temperature	Degrees F	109 Thermistor
Space Temperature	Degrees F	HOBO Logger/Ventostat
Space Relative Humidity	% RH	HOBO Logger/Ventostat

Parameter	Units	Device
Space Carbon Dioxide	ppm	Ventostat
Outside Air Temperature	Degrees F	Weather Station
Outside Relative Humidity	% RH	Weather Station

4.3.2) Parameters Monitored

Energy

- Monitored using a wattnode, a true RMS AC watt-hour transducer with pulse output (solid state relay closure) proportional to kWh consumed.

System Runtime

- Virtual measurement point based on the output from the wattnode. Determined by the amount of power that was being consumed by the unit.

First and second stage Burner Runtime

- 24VAC relays were used in parallel with the signal to the gas valve. The loggers monitored the status of the relay to determine if the gas valve was active. Multiple relays were used with multi-stage units.

Return air temperature

- Measured by a thermistor positioned in the return plenum.

Space temperature

- Measured by a HOBO logger placed at the thermostat.

Space relative humidity

- Measured by a HOBO logger placed at the thermostat.

Space CO2

- Measured by a Ventostat placed near the thermostat. Ventostats so they were rotated between sites, due to their limited quantity, to capture air quality measurements.

Outside Air temperature and relative humidity

- A weather station was placed at each test site to measure the outdoor air conditions.

4.3.3) Flip Flop Testing

Previous studies had documented the energy consumption characteristics of buildings with RTUs and then installed optimization packages to document the savings that resulted from their operation. This type of study requires a two year time span that makes it difficult to control for certain pre and post installation factors such as change in business, addition or subtraction of workers, and the typical up and down of business cycles. For this study, the research team selected a flip/flop testing protocol instead. This allowed for the capture of performance data in one year rather than two. The test design also assured that changes within the building would be accounted for in the performance of both the optimized operation and the basic operation. The study installed the necessary hardware to allow the RTUs to operate in both the basic mode and optimized or advanced mode of operation. Changes between modes were switched automatically by the data acquisition system and scheduled weekly to capture nearly the same activities within the building and nearly the same weather conditions outside the building. The ability to switch between modes of operation proved to be extremely valuable since there were a number of instances over the course of the monitoring period when the control of the RTU had to be switched back to basic operation due to problems with the advanced control.

5) DATA ANALYSIS

CEE partnered with PECI on this pilot research project. CEE was responsible for the overall project design and execution while PECI had the role of data analysis. CEE worked very closely with PECI on the data analysis and refined the results presented in this report.

5.1) Field Data Collection Methodology

5.1.1) Objectives

The advanced controls RTU pilot project was designed as a research study to evaluate the actual savings that could be achieved by retrofitting real-world systems with advanced controls. This required extensive monitoring and control technology to facilitate data collection and the ability to switch between modes of operation. CEE utilized a number of automated and manual data collection techniques to achieve the information required to assess the performance of the RTUs studied. The automated data collection system was primarily responsible for the performance data, including unit energy consumption and indicators of occupant comfort such as temperature and CO2 levels. The manual collection included the regular visits to document any changes to the space use at each site and the noting of changes to setpoints on any of the thermostatic devises (advanced or basic). This data was used to validate the performance data and to indicate change at the sites.

5.2) Data Analysis Methodology

52.1) Objectives

Detailed objectives for the data analysis phase of the project were developed in support of the overall goal of informing a CIP program for advanced RTU controls. The study prioritized primary and secondary objectives. Primary objectives were treated with a rigorous quantitative analysis approach; secondary objectives with a more qualitative analysis approach.

5.2.1.a) Primary Objectives

Estimate typical year energy savings as a result of adding advanced controls to tested units:

- Estimate electric and gas energy use for units with and without advanced controls enabled.
- Estimate energy savings for retrofitting each RTU with advanced controls.
- Compare savings estimates between the three technologies tested.
- Estimate the total energy savings for each site.

Quantify cost effectiveness based on energy savings estimates:

- Calculate simple payback based on estimated savings and total installed costs (less monitoring equipment) for each technology tested for a range of electric and gas energy costs.

Develop an energy savings calculator for advanced RTU controls:

- Develop an energy savings calculator that estimates energy and cost savings and simple payback for a proposed installation of advanced controls on existing RTUs that serve commercial buildings in Minnesota.

5.2.1.b) Secondary Objectives

Identify potential differences in indoor air quality and thermal comfort caused by advanced RTU controls:

- Analyze distribution of indoor air CO_2 concentrations with and without advanced controls enabled.
- Analyze distribution of indoor air temperatures with and without advanced controls enabled.

Determine whether there is an interaction between units with and without advanced controls in the same building:

- Estimate differences in energy consumption for control group units when advanced controls are enabled on other units compared to when basic controls are enabled.

Identify aspects of advanced control operation and outcomes unique to Minnesota's climate:

- Demonstrate actual results in Minnesota. Due to its colder climate and shorter cooling season compared to other regions, advanced controls tested in Minnesota may produce different savings than similar tests in other parts of the country.
- Use standard RTU operation practice as the baseline. Standard local practice is to run units intermittently with outside air dampers closed to reduce the temperature swings in the air delivered to the space, thereby minimizing excessive cold or warm outside air. While other tests define the baseline as a system that ventilates continuously per ventilation standards, this test's baseline was as-found conditions.

5.3) Energy Savings

The study used retrofit isolation approach as described in ASHRAE Guideline 14 §6.2[1] to measure energy use as well as other parameters listed in the monitoring plan in both basic and advanced operation modes. The experimental boundary was defined around each RTU included in the study. The team selected outside air temperature as the independent variable based on past experience and a factor screening technique. They selected measured electric energy use and estimated gas energy use based on gas valve

5.3.1) Model Specification

The team examined several alternative independent variables and analysis approaches before selecting the approach described in the following sections. They examined several potential independent variables, including outside air dry bulb temperature, outside air relative humidity, space temperature, space relative humidity, and space CO2 concentration. They assessed potential variables with a factor screening technique that created a multiple variable regression for one unit using all of the independent variable candidates. Outside air temperature was the only variable candidate with a significant effect at the 90% confidence level. This finding aligned with an initial hypothesis based on researchers' experience that RTU energy use depends on outside air temperature. Data aggregation to the hourly and daily levels was tested. Due to unexplained variation at the hourly level, the team selected daily aggregation for the analysis. They analyzed weekdays (Monday through Friday) separately from weekends (Saturday and Sunday) and holidays to account for dramatically different occupancy patterns.

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[1] ASHRAE. *Guideline 14-2002 Measurement of Energy and Demand Savings.* Section 6.2 Retrofit Isolation Approach. Atlanta, GA. 2002, June 22.

5.3.2) Data Preparation

Five minute interval test data was obtained for each RTU in the study. The following monitored data points were used for the energy savings analysis:

- Date and time.
- Advanced mode time on (fraction of time in Advanced mode per five minute interval).
- Gas valve Stage 1 run time fraction (fraction of time on per five minute interval).
- Gas valve Stage 2 run time fraction (fraction of time on per five minute interval).
- Electric energy use (kWh used in five minute interval).
- Outside air temperature (Average temperature for five minute interval).

Additionally, all hours for which data was considered valid were determined and indicated with a 1. Invalid hours were indicated with a 0. During valid hours, a unit and its monitoring system were operating as intended. Examples of invalid hours are:

- Hours when an RTU had a known operational issue.
- Hours when an RTU was shut down due to operational issues or service being performed.
- Hours when a monitoring system or sensor had a known operational issue.
- Hours with unusual readings outside of reasonable range.

Data was then imported into SAS analytics software[2] and the team performed the following data cleaning and conversion steps:

1. Variable naming conventions were made consistent for all RTUs.
2. Data was aggregated to one day time periods.
    a. Advanced mode time on averaged.
    b. Gas valve Stage 1 run time fraction was converted to daily run time fraction.
    c. Gas valve Stage 2 run time fraction was converted to daily run time fraction.
    d. Electric energy use was summed.
    e. Outside air temperature was averaged.
3. Data was cleaned to eliminate days with incomplete data.
    a. Days that were in Basic mode for part of the day and Advanced mode for part of the day were eliminated.
    b. Days that had data missing were eliminated.
    c. Days with invalid hours were eliminated.
4. Gas valve daily run time fraction was converted to approximate daily therms usage with Equation 1.

Equation 1. Conversion of Fractional Runtime to Therms

$$E = \frac{(T_1 \times C_1 + T_2 \times C_2) \times 24}{100{,}000}$$

Where:

$E = daily\ therms\ use$

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[2] SAS Enterprise Guide, Version 4.3 running Base SAS 9.2.

$$T_1 = stage\ 1\ daily\ runtime\ fraction$$
$$T_2 = stage\ 2\ daily\ runtime\ fraction$$
$$C_1 = stage\ 1\ rated\ capacity\ \left(\frac{Btu}{h}\right)$$
$$C_2 = stage\ 2\ rated\ capacity\ \left(\frac{Btu}{h}\right)$$
$$24 = hours\ per\ day$$
$$100{,}000 = Btu\ per\ therm$$

5.3.3) Regression Analysis

After preparing the data for regression analysis using the steps above, the team plotted daily energy use (kWh and therms) as a function of outside air temperature and fitted an initial regression to the data. They created separate regressions for gas and electric energy use during weekday or weekend operation in Basic or Advanced mode (eight regressions total for each RTU). Two RTUs (CEE RTU-3 and CEE RTU-4) had two optimization packages each installed. Those RTUs therefore operated in one of three modes, creating 12 regressions per RTU.

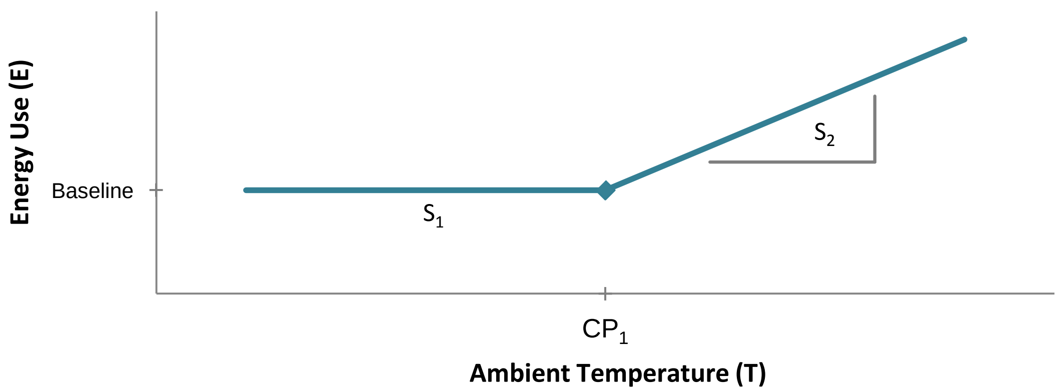
HVAC cooling energy use often displays strong temperature dependence at elevated temperatures, and a relatively constant response or subtle temperature dependence at lower temperatures. Heating energy typically has reversed behavior, with the strong temperature dependence at low temperatures and little to no temperature dependence at higher temperatures. Regression analyses of HVAC systems often use piece-wise linear regression (more simply referred to as a change point model) to describe this temperature dependence. A change point model selects the temperature at which energy use dependence on temperature changes (the change point), and determines an appropriate linear response above and below that point. Their forms are typically described by how many parameters (intercepts, slopes, and change points) are allowed to vary. For example, a three3 parameter (3P) change point model would be defined using one intercept, one change point, and one non-zero slope. Figure 4 and Figure 5 depict 3P change point models for electric and gas energy use, respectively.

Change point models are described in detail in ASHRAE 1050-RP. Equation 2 and Equation 3 provide the equation forms associated with each.

Equation 2. 3P Electric Equation Form

$$E(T) = \begin{cases} I_1, & T \le CP_1 \\ S_2 * T + I_2, & T > CP_1 \end{cases}$$

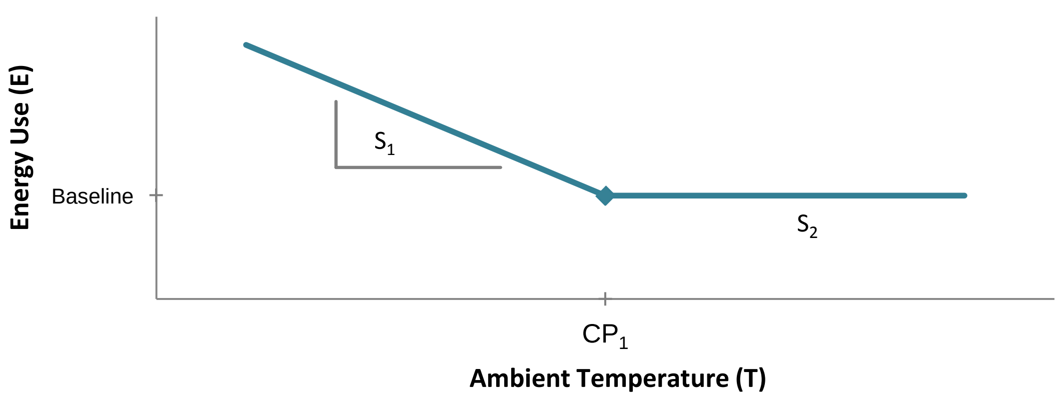
Figure 5. 3P Electric Model



Equation 3. 3P Gas Equation Form

$$E(T) = \begin{cases} S_1 * T + I_1, & T \le CP_1 \\ I_2 & T > CP_1 \end{cases}$$

Figure 6. 3P Gas Model

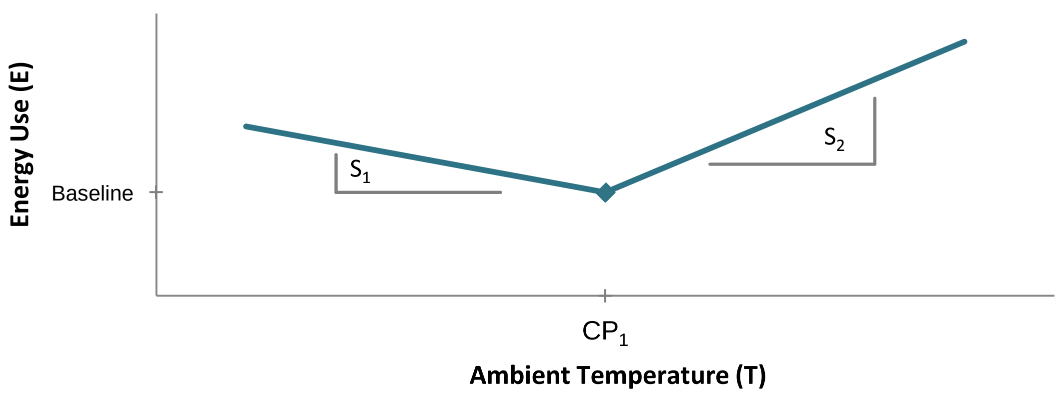


For RTUs with gas heat, such as the units in this study, it's reasonable to expect little to no temperature dependence at temperatures below the change point where cooling is not required. This is especially true for units that run the fan continuously at a constant speed whenever the space is occupied. If the fan operates intermittently or its speed is varied for different modes of operation, RTUs can also display temperature dependence at lower temperatures due to increased fan energy use for heating as temperatures decrease. To account for this dependence, the study also considered four parameter (4P) and five parameter (5P) models for electric energy use. Equation 4 and Equation 5, and Figure 7 and Figure 8, represent the functional form for electric 4P and 5P models, respectively.

Equation 4. 4P Electric Equation Form

$$E(T) = \begin{cases} S_1 * T + I_1, & T \leq CP_1 \\ S_2 * T + I_2, & T > CP_1 \end{cases}$$

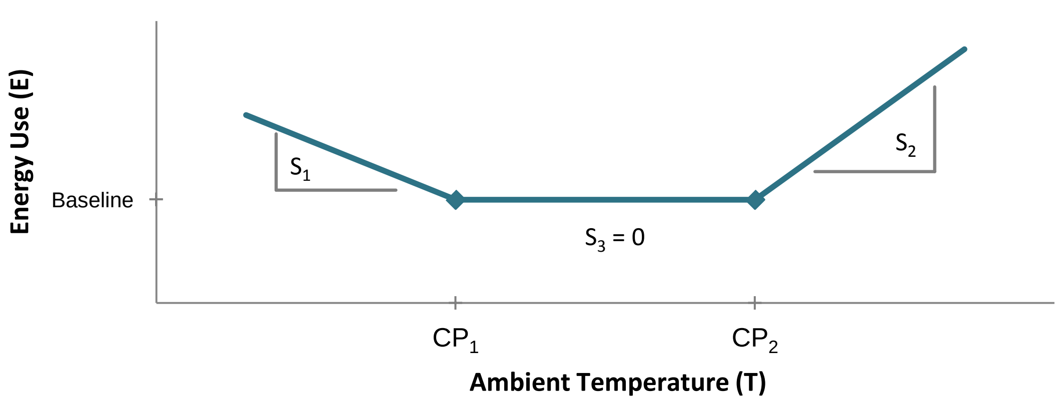
Figure 7. 4P Electric Model



Equation 5. 5P Electric Equation Form

$$E(T) = \begin{cases} S_1 * T + I_1, & T \leq CP_1 \\ S_2 * T + I_2, & CP_1 < T \leq CP_2 \\ S_3 * T + I_3, & T > CP_2 \end{cases}$$

Figure 8. 5P Electric Model



The team selected electric energy use regression forms for each model based on visual inspection as well as comparison of coefficient of determination (R^2) for the forms tested (3P, 4P, or 5P). For each electric energy use regression, the team chose the best-fitting model with a physically plausible form.

They selected 3P change point models for all gas energy use models, as gas use was not expected or observed to show temperature dependence above the single change point temperature.

The data analysts created all the 3P and 4P models in a batch analysis procedure using SAS analytics software. They selected parameter coefficients for 3P and 4P models with a Markov Chain Monte Carlo statistical algorithm[3] that minimizes total error. 5P models were created individually using the ECAM[4] plug in for Excel, which uses a methodology for determining parameter coefficients consistent with those documented in ASHRAE 1050-RP, *Development of a Toolkit for Calculating Linear, Change-point Linear and Multiple-Linear Inverse Building Energy Analysis Models*.

Some models were eliminated from consideration in the analysis outcomes due to one or more of the following reasons:

- Not enough valid data points available to create an acceptable regression.
- Temperature range of available data too narrow to extrapolate to annual estimates.
- Energy use, not temperature dependent, alternate independent variable(s) not available.
- Improper unit operation.

A list of models that were eliminated from consideration in analysis outcomes is included in Appendix C. Each RTU or group of RTUs is documented for the reason for their exclusion.

5.4) Typical Weather Year Normalization

After final regression models were selected and developed they were each normalized using NOAA Typical Meteorological Year (TMY3) data for Minneapolis to estimate energy use for a typical weather year. 2014 was used as the reference year to assign day of the week and holidays to the TMY3 data. Energy use for Monday through Friday was estimated using the weekday (or "occupied") regressions. Energy use for Saturday, Sunday, and holidays was estimated using the weekend (or "unoccupied) regressions. Daily estimates were then summed for the year to arrive at annual estimates. Estimated annual energy use was calculated for Basic and Advanced mode operation for both electric gas energy use. Energy savings were calculated by subtracting advanced mode use from basic mode use.

5.5) Uncertainty Analysis

Regression analysis uncertainty can come from multiple sources, the primary two being measurement uncertainty and regression model uncertainty. Both can impact final energy use estimates, but measurement uncertainty does not affect energy savings estimates because using the same instrumentation for both cases typically eliminates bias error when examining the difference between two energy use cases. And selecting measurement equipment with an appropriate level of precision minimizes random measurement error.

Regression model uncertainty is far more important in this type of analysis, because it describes how much of the energy use response cannot be explained by the model, and would typically occur even if measurement were perfect. Variables outside the scope of the study, such as occupancy, occupant thermostat interventions, and the effect of other unmonitored units on the building, can all impact the degree to which the model is able to describe actual measured energy use. This section therefore focuses on regression model uncertainty.

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[3] SAS, Inc, 2014: SAS/STAT® 9.3 User's Guide. "MCMC Procedure, Example 54.10: Change Point Models." Accessed 4/23/2014 at http://support.sas.com/documentation/cdl/en/statug/63962/HTML/default/viewer.htm#statug_mcmc_sect057.htm

[4] Energy Charting and Metrics Tool ECAM+ v3.0. Accessed 4/24/2014 at http://buildingretuning.pnnl.gov/ecam.stm

To quantify the uncertainty surrounding energy savings estimates, research staff chose a confidence level of 90 percent and constructed upper and lower confidence limits around the energy savings estimates using the Equation 6 and Equation 7.

Equation 6. Upper Confidence Limit individual units

$$CL_u = S + CE * z$$

Equation 7. Lower Confidence Limit individual units

$$CL_l = S - CE * z$$

Where:
$CL_u = upper\ confidence\ limit$
$CL_l = lower\ confidence\ limit$
$S = normalized\ savings\ estimate$
$CE = combined\ error = \sqrt{RMSE_b^2 + RMSE_a^2}$
$RMSE_b = Root\ Mean\ Square\ Error\ basic\ regressions$
$RMSE_a = Root\ Mean\ Square\ Error\ advanced\ regressions$
$z = z\ score\ of\ 1.645\ for\ 90\%\ confidence\ interval$

This means that 90 percent of the samples would display savings within the upper and lower confidence limits. For each model, if the confidence interval does not band zero the result (positive or negative savings) are considered to be statistically significant.

To determine upper and lower confidence limits for technology groups and sites, the combined error for each group was added using a simple summation, which assumes that the combined errors associated with each unit are not independent. The team chose this assumption because the analysis indicated interaction between units in the same building. Therefore, error cannot be assumed to be independent.

Equation 8 and Equation 9 describe the calculation of upper and lower confidence limits for savings aggregated by technology group and site.

Equation 8. Upper Confidence Limit Aggregated

$$CL_u = S_T + CE_T * z$$

Equation 9. Lower Confidence Limit Aggregated

$$CL_l = S_T - CE_T * z$$

Where:
$CL_u = upper\ confidence\ limit$
$CL_l = lower\ confidence\ limit$
$S_T = aggregated\ normalized\ savings\ estimate$
$CE_T = total\ combined\ error = \sum CE$
$z = z\ score\ of\ 1.645\ for\ 90\%\ confidence\ interval$

5.6) Energy Savings Calculator

The study developed a calculator to estimate electric and gas energy savings and simple payback period after applying any of the three control packages to one or more RTUs on a Minnesota building. Savings were estimated using the regression equations developed in the study.

The calculator applies to existing rooftop air conditioning units with gas heat serving existing commercial buildings. It was developed based on the results of this study, which included units ranging from two to 15 tons that serve spaces with typical occupied hours from 9AM to 5PM, Monday through Friday. It is most accurate when applied to similar scenarios. Additional discretion should be used when applying the calculator to units with different capacities, those that serve spaces with occupied hours that differ from those in the study, or those with unusually high or low loads. The calculator uses the following user inputs to generate a custom savings estimate:

- Nearest city (Detroit Lakes, Duluth, Minneapolis-St Paul, Rochester, Worthington).
- Days open (number of days facility is open or occupied per week)[5].
- Technology (Catalyst, Digi RTU, Prem vent).
- Nominal heating capacity (BTU/hr).
- Nominal cooling capacity (tons).
- Average electricity cost ($/kWh blended electric rate)[6].
- Average gas cost ($/therm blended gas rate).
- Estimated labor cost ($).
- Estimated equipment cost ($).

It then calculates the following output parameters:

- Cooling savings (kWh/yr).
- Heating savings (therms/yr).
- Simple payback (years).
- Total costs ($).
- Avoided electric costs ($ per year).
- Avoided gas costs ($ per year).

The calculator savings are weather-normalized estimates that scale with the user-input cooling and heating capacity. The results are also normalized to the average baseline energy use per rated ton of cooling capacity observed in the study. The calculator uses the following procedure to estimate electric and gas energy savings and simple payback:

1. Evaluate regressions for all units in the study with advanced controls, using the average daily temperatures for the Typical Meteorological Year weather data for the location specified. 2014 serves as the reference year to determine the day of the week, and the calendar assumes first

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[5] Hours/day at sites was not used in order to simplify model for calculations purposes.

[6] For the purpose of a simplified calculator, blended rates were used. If a more detailed analysis is desired, the actual rate along with potential for demand savings as a result of overs-sizing could be factored in

open day per week is Monday. It assumes open days are consecutive. The regressions are evaluated as follows:
   a. The occupied baseline and retrofit regressions are evaluated for days open.
   b. The unoccupied baseline and retrofit regressions are evaluated for days closed.
2. Sum the estimated daily energy use for the baseline and retrofit case for each RTU, yielding estimated annual baseline and retrofit energy use.
3. Divide the estimated annual energy use for each RTU by the corresponding heating or cooling capacity for each RTU, yielding capacity-normalized energy use (therms per BTUh per year, and kWh per ton per year) for the baseline and retrofit case for each RTU.
4. Average the capacity-normalized energy use for each RTU with the selected technology, yielding the average capacity-normalized energy use for the baseline and retrofit in the climate specified.
5. Divide the capacity-normalized baseline energy use for each technology by the overall study capacity-normalized baseline use to develop a baseline use normalization factor for each technology type.
6. Determine the difference between the baseline and retrofit, yielding the capacity-normalized energy savings.
7. Multiply capacity-normalized energy savings by the appropriate baseline use normalization factor for the technology.
8. Multiply the capacity-normalized electric and gas energy savings by the corresponding heating and cooling capacity input in the calculator, yielding the estimated electric and gas energy savings for the specific site.
9. Calculate the estimated simple payback in years using the following formula:

$$Simple\ Payback = \frac{labor\ cost(\$) + equipment\ cost(\$)}{electric\ savings(kWh) \times electricity\ cost\left(\frac{\$}{kWh}\right) + gas\ savings(therms) \times gas\ cost\left(\frac{\$}{therm}\right)}$$

5.7) Cost Effectiveness

The project team analyzed the cost-effectiveness of each technology type studied, using simple payback as the metric and an upper threshold of five years to be deemed cost effective. Five years was the upper limit because this technology is intended as a retrofit for existing units typically assumed to have a useful life of 15 years.

Additional analysis was performed to examine the impact of baseline energy use and RTU cooling capacity on cost effectiveness. To determine how baseline energy use affects simple payback , the study assumed that energy savings as a percentage of baseline use would remain consistent regardless of baseline use, and projected simple payback for each technology for a range of baseline scenarios. To determine the impact of system capacity, the study assumed that the cost to capacity ratio would improve (decrease) as system capacities increased, and that the ratio of energy savings to system capacity would remain consistent with increasing system capacities.

The project team analyzed cost data gathered over the course of the study to compare the three technology types and obtained Catalyst and DigiRTU manufacturer cost estimates for three hypothetical projects:

- Small – three units totaling 29.5 tons.
- Standard – 10 units totaling 94 tons.
- Large – 25 units totaling 247 tons.

There were three different costs provided for the Catalyst system. A "Standalone" cost was provided for the controller only, which is the minimum requirement to realize energy savings benefits. Optional features for recording data were also priced including: "Catalyst Cloud", which reports data to an online database through a building's existing internet service, and "Catalyst eIQ w/ Verizon", which reports data to an online database through a cellular modem. The as-tested version was "Catalyst eIQ w/ Verizon".

For Premium Ventilation actual project costs were used. The cost per RTU for the MDH site (20 RTUs) of $3,092 was used as a proxy for the "Large" site scenario. The cost per RTU for the NUR site (7 RTUs) of $3,759 was used as a proxy for the "Medium" site scenario. KMC cost for the "Small" site scenario was estimated at $4,000 per RTU.

Based on the data sources and assumptions described, the cost for each technology is summarized in Table 7. Cost Data, which gives cost data per site, per RTU, and per cooling ton. For simple payback period analysis costs for a "Standard" site were used. For Catalyst the pricing for the "Standalone" system was used since the additional features for other versions are not necessary for realization of energy savings.

Table 7. Cost Data

Estimated Project Cost

Site Size Category	Number of Units	Tons of Cooling	Digi-RTU Cost	Catalyst Standalone	Catalyst Cloud	Catalyst eIQ w/ Verizon	Prem Vent
Small	3	29.5	$15,782	$11,061	$15,963	$21,450	$12,000
Standard	10	94	$47,447	$36,480	$47,050	$53,020	$37,590
Large	25	247	$122,024	$87,525	$109,125	$111,375	$77,300

Estimated Cost Per Unit

Site Size Category	Number of Units	Tons of Cooling	Digi-RTU Cost	Catalyst Standalone	Catalyst Cloud	Catalyst eIQ w/ Verizon	Prem Vent
Small	3	29.5	$5,261	$3,687	$5,321	$7,150	$4,000
Standard	10	94	$4,745	$3,648	$4,705	$5,302	$3,759
Large	25	247	$4,881	$3,501	$4,365	$4,455	$3,092

Estimated Cost Per Ton

Site Size Category	Number of Units	Tons of Cooling	Digi-RTU Cost	Catalyst Standalone	Catalyst Cloud	Catalyst eIQ w/ Verizon	Prem Vent
Small	3	29.5	$535	$375	$541	$727	$407
Standard	10	94	$505	$388	$501	$564	$400
Large	25	247	$494	$354	$442	$451	$313

Note: DigiRTU and Catalyst estimates are based on manufacturer provided estimates. Premium Ventilation estimates are based on actual costs incurred during test.

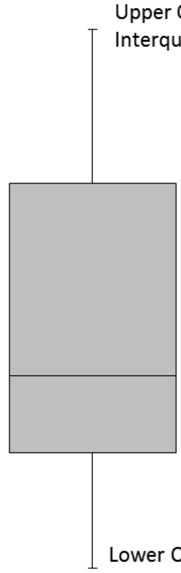
5.8) Other Impacts

In addition to energy impacts, the team also performed analysis on space temperature, indoor air quality, and interaction with units that were monitored but did not have advanced controls installed (i.e. "control units").

5.8.1) Space Temperature

Space temperature with and without advanced controls was visually compared using outlier box-and-whisker plots (see Figure 9). Space temperature is considered an indicator of thermal comfort, and the researchers wanted to understand whether advanced controls could negatively or positively impact thermal comfort.

Figure 9. Outlier Box-and-Whisker Plot



5.8.2) Indoor Air Quality

To examine how each technology could impact indoor air quality, using box-and-whisker diagrams staff compared CO_2 concentration with and without the advanced controls enabled. CO_2 concentration is an indicator of number of occupants in the space, and is used as an indicator of other potential contaminants. The team constrained the analysis to what could be considered occupied, fully operational hours. Hours from 9AM to 5PM on weekdays were used for all sites.

5.8.3) Interaction with Control Units

To determine whether there is an interactive effect between units that receive an advanced control upgrade and units that did not, the team analyzed energy use data of some units at the test sites that did not receive an advanced controls upgrade. They completed an energy savings analysis as described above, with the hypothesis that if no interaction was observed, there would not be a statistically significant difference in energy use between periods when other units were in advanced mode compared to when other units were in basic mode.

6) RESULTS

The results section will present the energy savings by site and technology, the cost effectiveness and the effects of unit size on the payback period for all sites monitored. Additionally there is a discussion of the monitored data for space conditions and if the advanced mode and basic mode maintained the space at the same level of comfort and indoor air quality.

6.1) Primary Site Overview

The Advanced Rooftop Controls Project tested a total of 60 rooftop units (RTUs) that span over six different sites ranging from 16,000 to 64,000 square feet. All of the sites are commercial buildings that have a variety of different space types including offices, cubicles, conference rooms, manufacturing areas, and warehouse/storage areas. The space utilization remained fairly stable throughout the sites, with the biggest variance being conference rooms which were often used sparingly and not on a regular schedule. Details of each site can be found in Appendix B.

The pilot study did lose one of the test sites due to the site's refusal to renew their lease. The MDH site was the last to get fully instrumented with the Premium Ventilation control, and ended its lease with the property management firm five months before the end of the data collection period. This resulted in limited performance data for this site, and the study was unable to collect historic energy consumption for reference purposes.

The rooftop units in the study varied from three to 15 tons, and included the following manufacturers: Lennox, Bryant, Trane, and Carrier. All were packaged units that provided both heating and cooling and used natural gas for their primary fuel for heating. Aside from the CEE site, the spaces were conditioned completely by the RTUs. Table 8 provides a summary of each site.

Table 8. Overview of the Six Test Sites in the Project

Site	# of Units	Optimization Package	Monitoring Start Date	Optimization Start Date	End of data collection
CEE	7	Digi-RTU/KMC	8/11/2011	3/14/2012	8/31/2013
NUR	9	KMC	1/5/2012	7/30/2012	8/31/2013
MIN	12	Catalyst	3/12/2012	7/31/2012	8/31/2013
NOW	3	Digi-RTU	3/30/2012	6/14/2012	8/31/2013
MDH	20	KMC	3/30/2012	8/13/2012	3/27/2013
SEI	9	Digi-RTU	4/26/2012	6/13/2012	8/31/2013

6.2) Additional Site

After losing the MDH site, CEE worked with the manufacturer of the Catalyst controller and the local installer of the Catalyst product to recruit another site for monitoring. The YAL site was brought into the pilot very late in the monitoring period, so the project only collected and processed summer cooling season data. CEE was able to collect performance data from the YAL site without the deployment of the monitoring system that was used at other test sites. Data was collected from the Catalyst web interface and processed to yield performance data required for evaluation. Because there were only six Catalyst controllers in the pilot project in the initial stage, the expansion of the sample size with the addition of the YAL site, helped define the savings numbers that could be reported. Table 9 provides details on the YAL site.

Table 9. Overview of Additional Limited Data Site

Site	# of Units	Optimization Package	Monitoring Start Date	Optimization Start Date	End of data collection
YAL	6	Catalyst	7/2/2013	7/2/2013	12/21/2013

6.3) RTU Characterization

This pilot project monitored 60 RTUs for energy consumption. Two RTUs had multiple optimization packages installed, so the total sample size for monitored performance data was 62 RTUs. Of the 62 in the data set, the study monitored ten as a control group with no optimization packages installed. Figure 10 displays the distribution of cooling capacity for all the RTUs monitored in the project. There is a reasonable spread of RTU sizes ranging from two to 15 tons. Figure 11 displays the breakdown of RTU sizes by optimization type.

Figure 10. Distribution of RTU Cooling Capacity

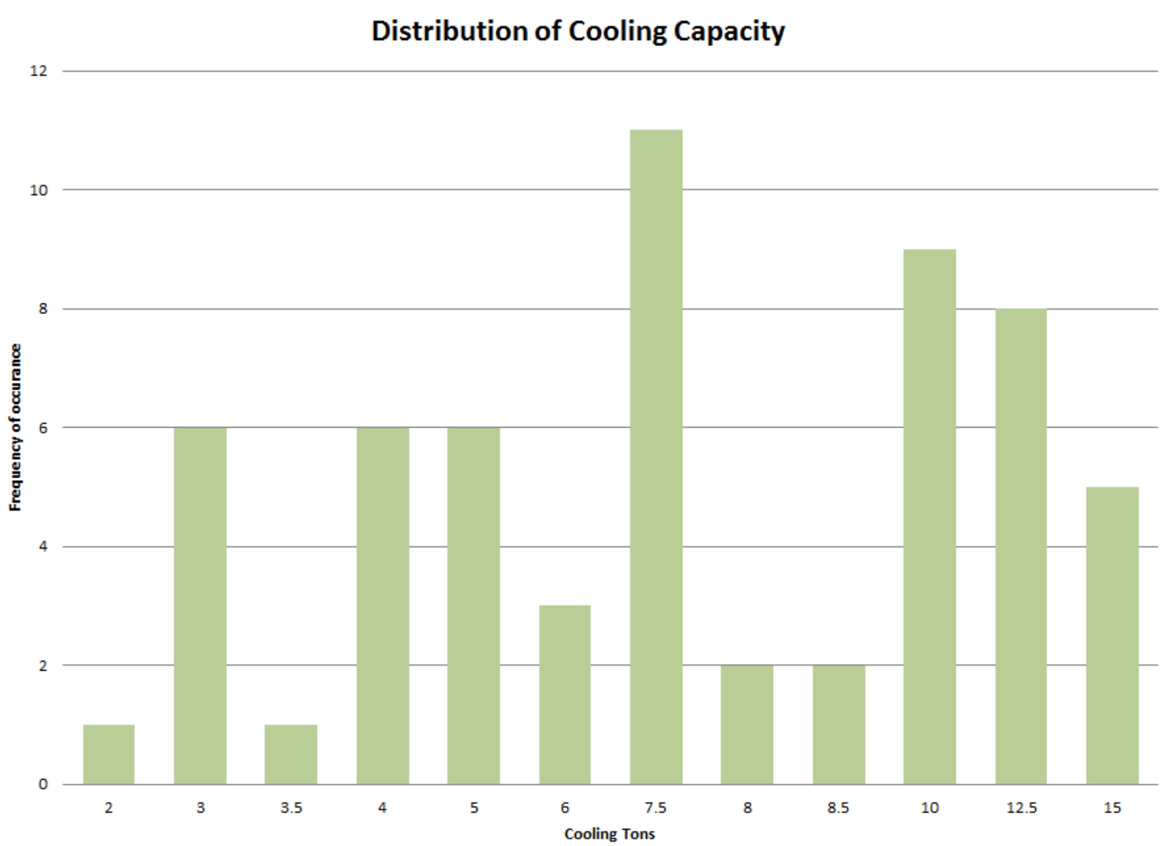
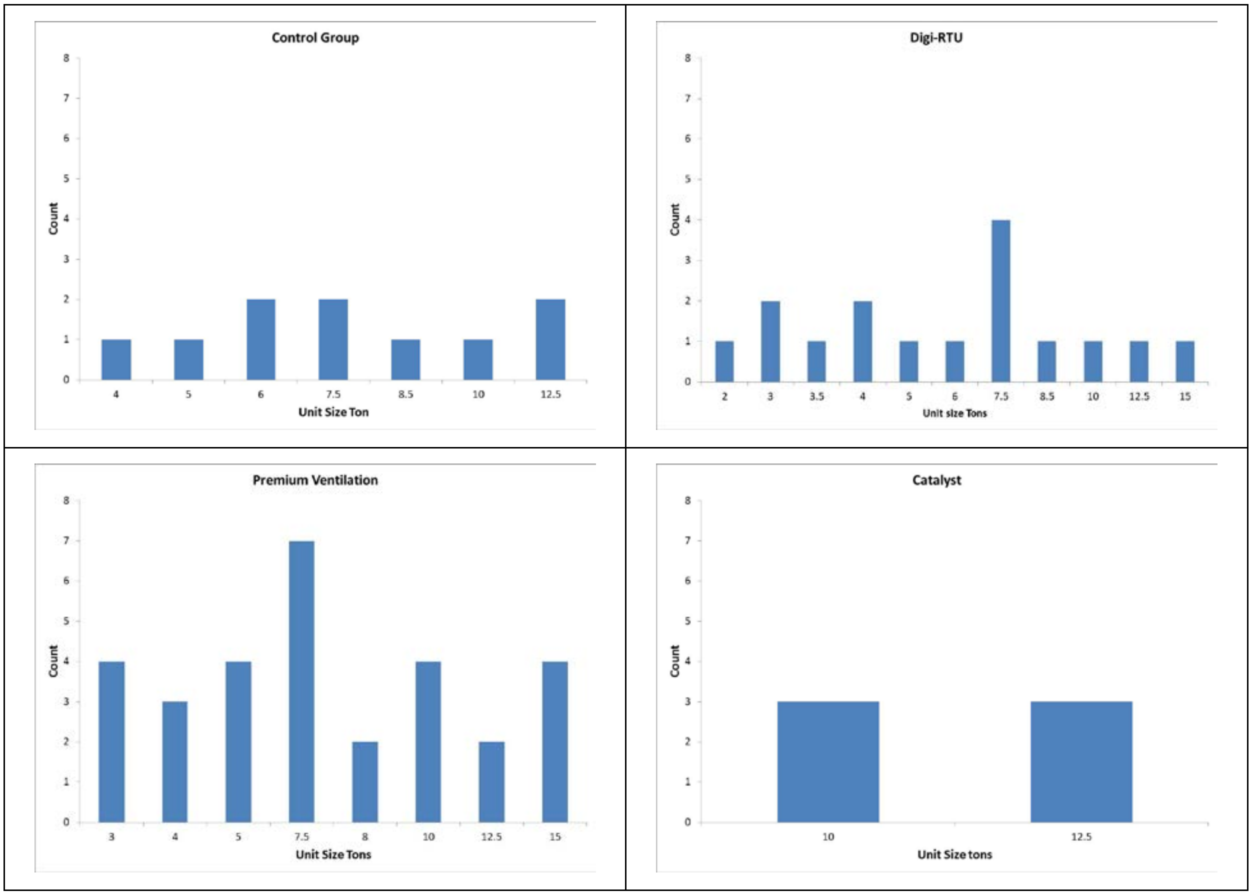


Figure 11. Distribution of RTU Size by Advance Control Technology



6.4) Market Transformation

From the time of installation to writing this report, all of the optimization packages studied went through a number of advances. While this can be expected, the speed at which the development has happened was of interest for this study.

Proposal development for the Advanced Rooftop HVAC Unit Control Pilot CARD grant began in October of 2011. As part of the development for the application to the CARD grant, staff performed research to generate a list of potential optimization packages to include in the pilot study. The research team interviewed potential suppliers of advanced controls and performed site visits to research the packages, with the intent to select the packages that were the most ready to go to market with their product. At the onset of the project, two packages appeared to be the best candidates for the study: the Premium Ventilation package and the Digi-RTU optimizer. The team added a third advanced control package, the Catalyst controller, given its market readiness and the availability of a test site to apply it to. The research team installed the most current version of each technology, with the intent of documenting the savings claimed by their manufactures.

During the research project, which spanned almost three years, each manufacturer continued to develop their products and enhance their offerings. These enhancements could be categorized into 3 groups; Functional, System, and Installation. Functional enhancements include a number of new features that bring value to the information provided by the systems. These features include fault detection, increased visibility of system parameters and control of additional functions previously integral to the RTU such as the economizer section. System enhancements made components smaller and reduced the footprint of the optimization package in order to reduce the cost of the optimization. Installation enhancement parallel system enhancements, but focused on installing the packages more quickly, with a limited number of additional enclosures and reduced wiring requirements.

As a result, the advanced control packages studied by this pilot research project do not currently exist as a product offering by two of the three manufactures. Each still offers its fundamental control theories in its newest version, but the current versions include improved packaging and the ability to provide additional options.

6.5) Energy Savings

All advanced controls packages produced statistically significant electric energy savings at the 90 percent confidence level. As a percentage of baseline RTU energy use, the Catalyst and Digi-RTU controls both achieved approximately 30 percent electric energy savings, and the Premium Ventilation achieved approximately 15 percent electric energy savings. In aggregate, control units realized negative electric energy savings, indicating that advanced controls could create an interactive effect on units that are not upgraded. This interaction suggests that it may be best practice to upgrade all RTUs on a given building to avoid increasing the energy use of units that do not receive upgrades.

Gas energy savings were significantly more variable than electric energy savings. Catalyst and Digi-RTU resulted in statistically significant negative gas energy savings. However, there is a high degree of variability in the individual estimates, reflected in the wide confidence intervals around the estimates. The Premium Ventilation and control units also resulted in negative gas savings estimates, but the results are not statistically significant at the 90 percent confidence level.

Electric energy savings offset negative gas energy savings on a cost basis using typical electric and gas energy rates, achieving a net financial benefit.

Individual units and functional groups displayed a fairly high level of variability across the study, which may be related to the baseline definition for this study - the as-found operating conditions of the units. Project staff found many units operating with the supply fan running intermittently with calls for cooling or heating during occupied hours, and with a fully closed minimum outdoor air damper position. Although this operation is not code compliant, it is common in the Minnesota climate due to extreme temperatures and the cycling nature of RTUs, whereby if the supply fan was operating while the cooling or heating was inactive, discharge air temperatures would swing excessively, impacting occupant comfort. These conditions remained constant during the course of the study.

Figure 12 and Figure 13 show estimated electric and gas energy savings predicted for a typical year with upper and lower 90 percent confidence limits for each technology and for control units (“None”).

Figure 12. Electric Energy Savings by Technology

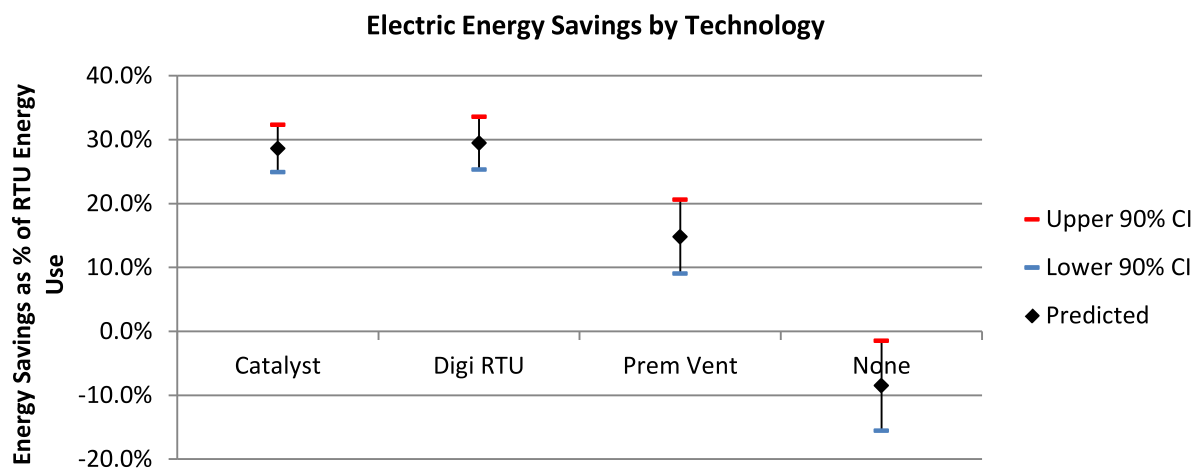
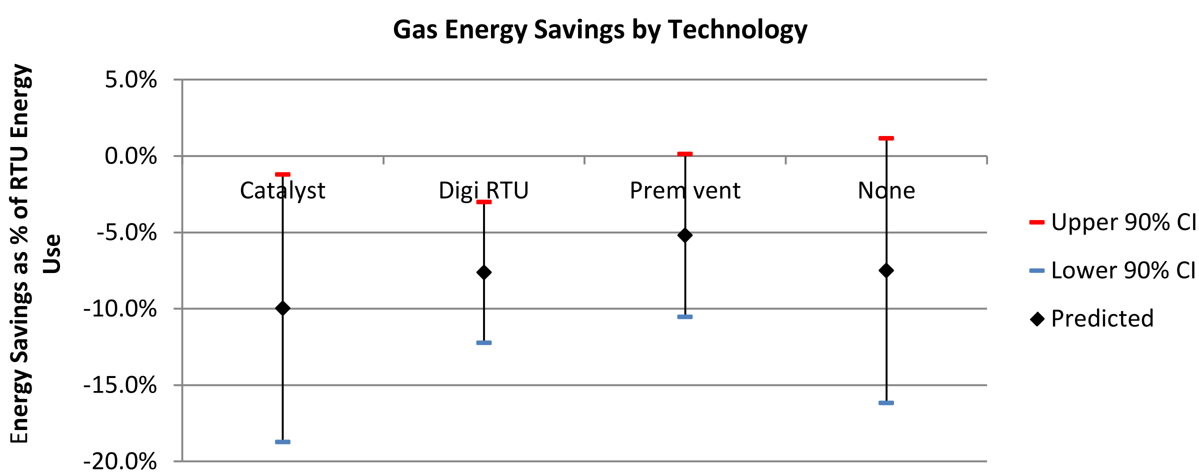


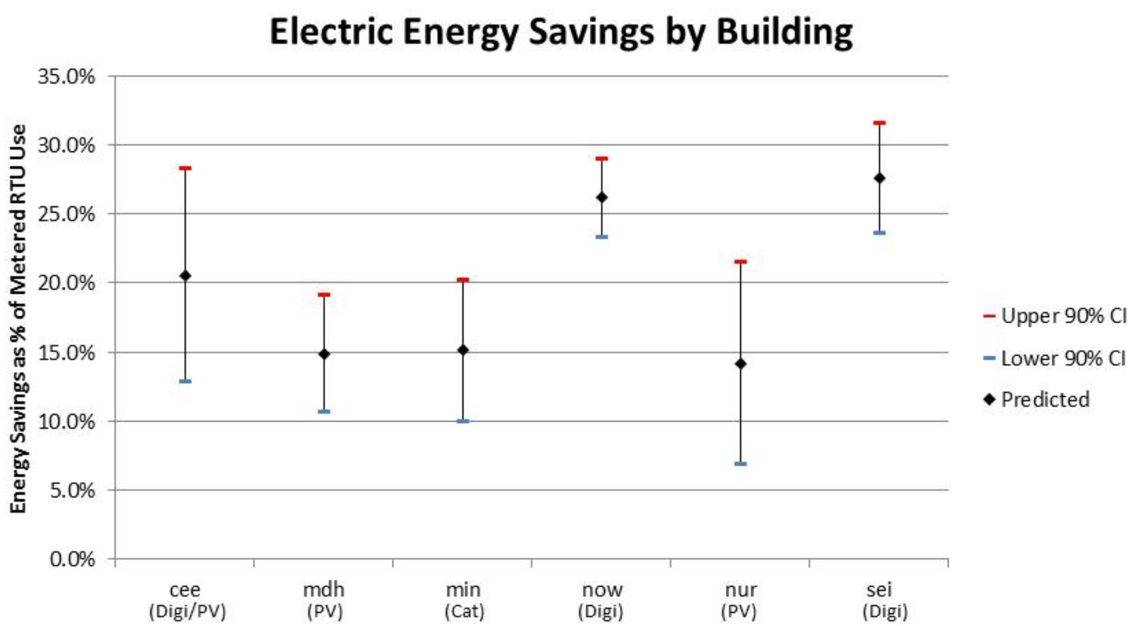
Figure 13. Gas Energy Savings by Technology



Reviewing the electric energy savings by building (Figure 14), shows that all buildings in the study achieved statistically significant electricity savings. The optimization type is displayed below the building name

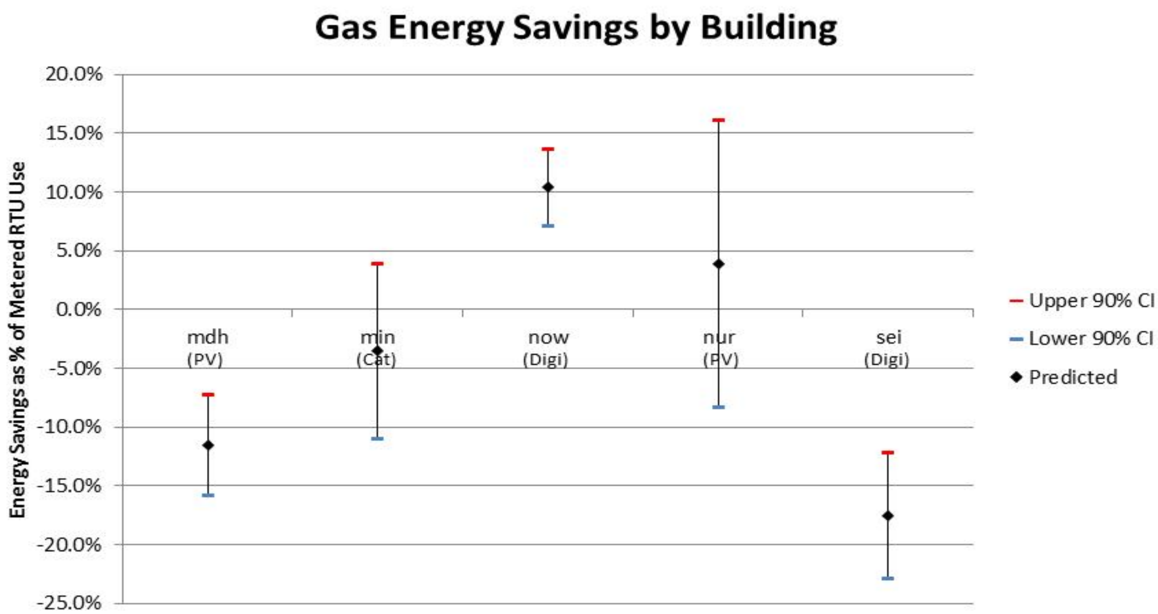
*Note that generally, the aggregated building level electric energy savings estimates are lower than the aggregated technology estimates for the technology or technologies installed at a particular site. This is due to the negative savings impacts of control units that were monitored and analyzed.

Figure 14. Electric Energy Savings by Building



Gas energy savings aggregated to the building level displayed a high degree of variability (Figure 15). The MDH and SEI sites realized statistically significant negative gas savings. The NOW site realized statistically significant positive gas savings. The MIN and NUR sites did not realize statistically significant savings. The CEE site is not reported in this analysis due to a central hot water system that supplied supplemental heat in addition to the RTU which could not be accurately sub metered and accounted for.

Figure 15. Gas Energy Savings by Building



Appendix D shows electric energy savings results at the unit (or functional group) level. The graphs display a high degree of variability between individual units. The Catalyst technology consistently produced savings in the range of 20 percent to 40 percent of baseline energy use. The Digi-RTU technology produced savings in the range of 40 percent to 50 percent for some units, but also resulted in lower savings in the 20 percent range for some units, and negative savings of approximately -50 percent for one unit. The Premium Ventilation savings displayed the widest variation from approximately negative 50 percent to positive 60 percent. All control units displayed negative energy savings during times when other units were operating with advanced controls, except for one unit which displayed positive energy savings during advanced operation.

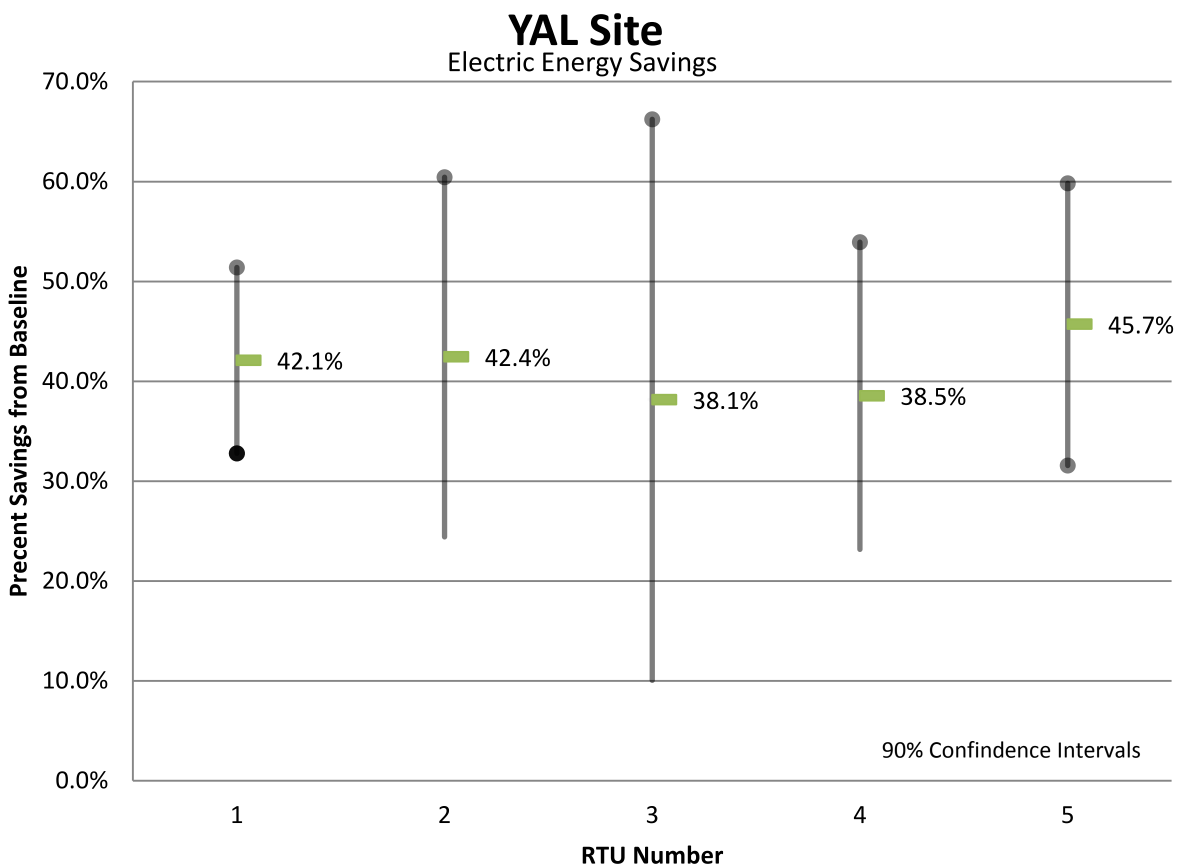
Gas savings at the unit level are also included in Appendix D. Gas savings were even more variable than electric savings, and were mostly negative. The Premium Ventilation produced the most variable gas savings, ranging from approximately -100 percent to approximately positive 55 percent.

Appendix D also includes absolute values for normalized annual energy use, savings for each RTU, and the confidence interval for the savings estimates.

6.5.1) Energy Savings Documented from the YAL Site

The five RTUs at the YAL site were not processed by the SAS software package. That site's data was only available from the Catalyst web portal that collected one-minute performance data on all the units. CEE processed the data into daily consumption values and applied a 5P model to the electric consumption information. Only cooling energy was available for processing, so heating results will not be reported. The 5P models were generated with the ECAM plugin for Excel. The electrical savings results are very much in line with those reported for the six other Catalyst units in the study. Savings averaged 38.8 percent at the 90 percent confidence level. The average savings was higher than previously reported by the other Catalyst site in this study (site MIN), with a much wider confidence interval which could have resulted from a limited data set that didn't span an entire year. Figure 16 displays the representation of the unit savings.

Figure 16. Electric Savings for the YAL Site

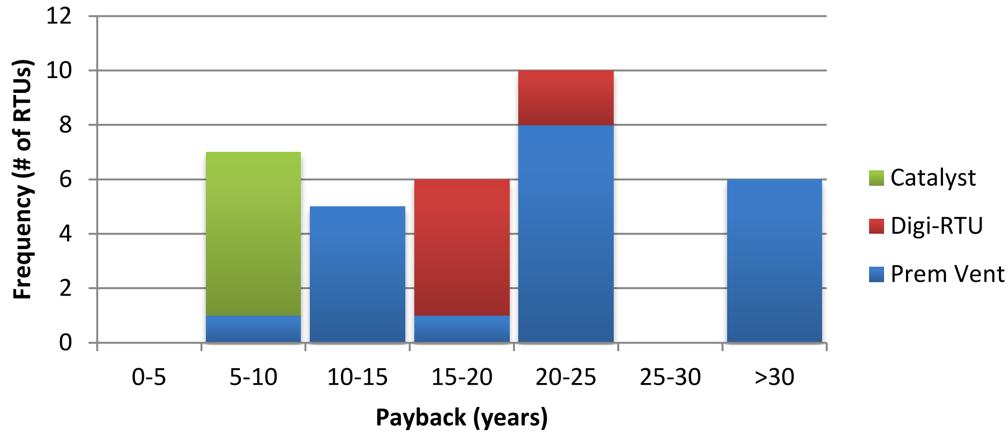


6.6) Cost Effectiveness

Under the conditions of the test, none of the technologies achieved energy savings that could be considered cost effective using a simple payback of five years as the upper threshold. However, several variables could decrease the payback. Higher baseline energy use than observed in the study would make the controls retrofit more cost-effective. Most of the units in the study served areas with relatively low occupant densities. Higher occupant densities (e.g. retail spaces or places of assembly) and/or lighting and equipment loads may substantially increase baseline energy use and savings, decreasing payback. All units in the study had cooling capacities of less than or equal to 15 tons, with an average of 7.8 tons. Application of the technologies to larger units would improve cost effectiveness. Longer building operating hours would also be likely to improve cost-effectiveness. Buildings in the study generally operated from 9AM to 5PM, Monday through Friday.

Cost effectiveness varied greatly across the study, but all paybacks exceeded five years. Figure 17 shows frequency of RTUs by payback range and technology.

Figure 17. RTU Frequency by Payback Range and Technology



To understand primary drivers of payback estimates for units in the study, the team performed additional analysis to determine the differences between consumption and savings for each type of technology. This analysis found that per rated ton of cooling capacity both the Catalyst and Digi-RTU achieved savings of approximately 30 percent of electric use, and Premium Ventilation achieved savings of approximately 15 percent of electric us. Units that received the Catalyst upgrade used the most electric energy per ton of rated cooling capacity in the baseline, followed by units that received the Digi-RTU upgrade, and finally by units that received the Premium Ventilation upgrade. Gas use per rated ton displayed less variation than electric use per rated ton. Units with Digi-RTU used the most gas per rated ton, followed by units with Premium Ventilation, then units with Catalyst. The wide variation in baseline energy use may be due to a number of factors, including varying space use types (including open office, closed office, conference rooms, light manufacturing, and shipping and receiving). Another potential explanation of the wide variability is likely the definition of the baseline for the study, which examined units as-found. Other research[7] on similar technologies has defined the baseline as a well-maintained system continuously providing code-compliant ventilation during occupied hours. Figure 18 and Figure 19 compare baseline electric and gas energy use per ton to savings per ton across the three technologies.

[7] PNNL. *Advanced Rooftop Control (ARC) Retrofit: Field-Test Results.* July 2013. Retrieved 5/2/2014 from http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22656.pdf

Figure 18. Electric Energy Use and Savings per Rated Ton Cooling Capacity

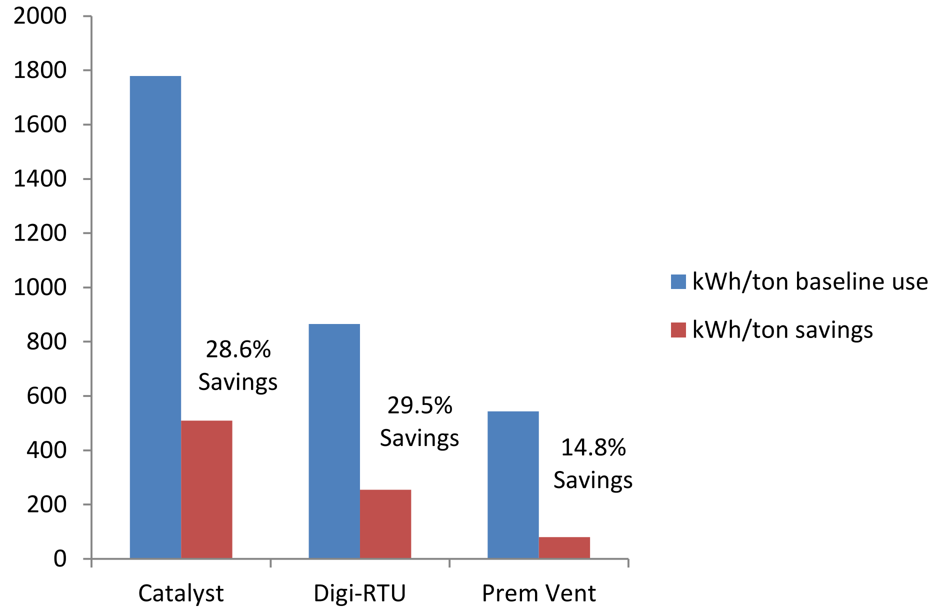
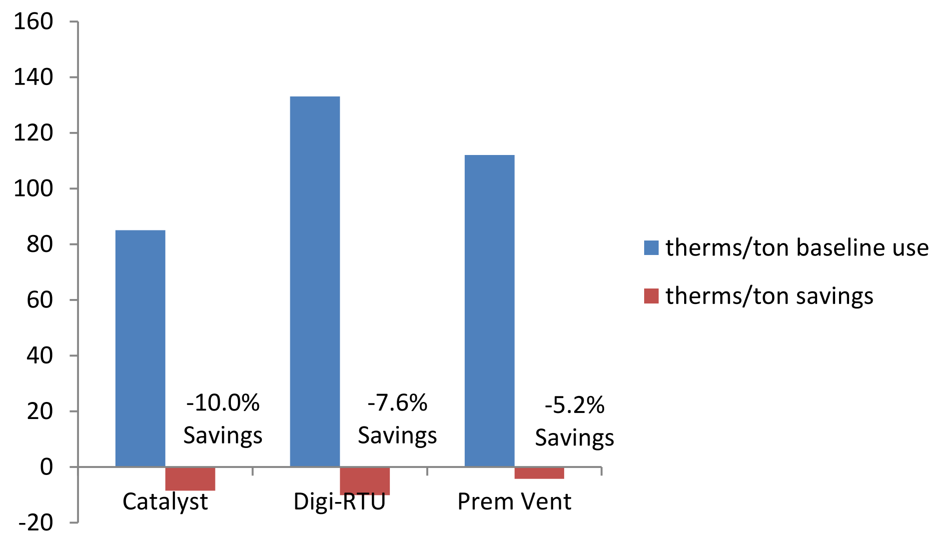
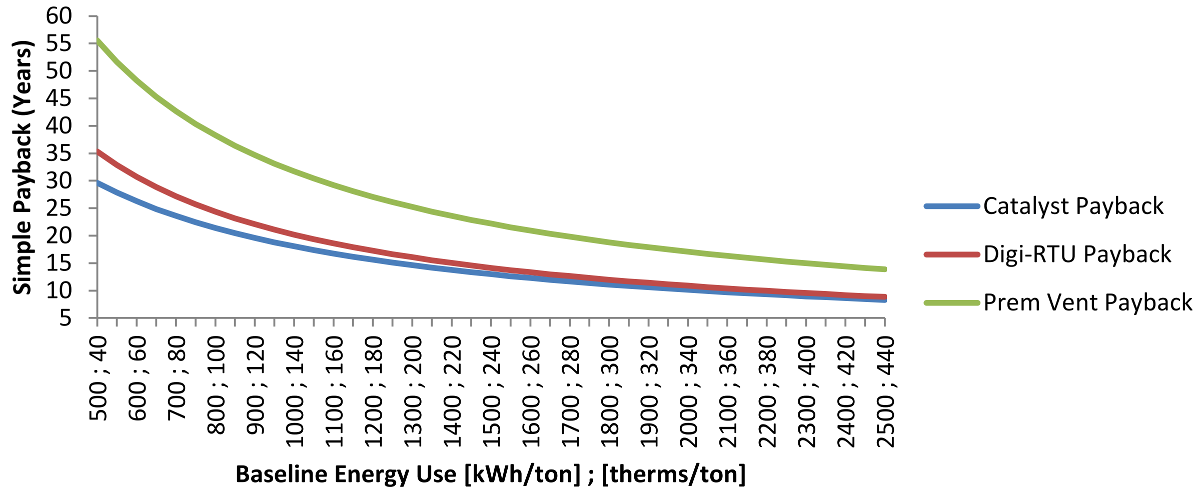


Figure 19. Gas Energy Use and Savings per Rated Ton Cooling Capacity



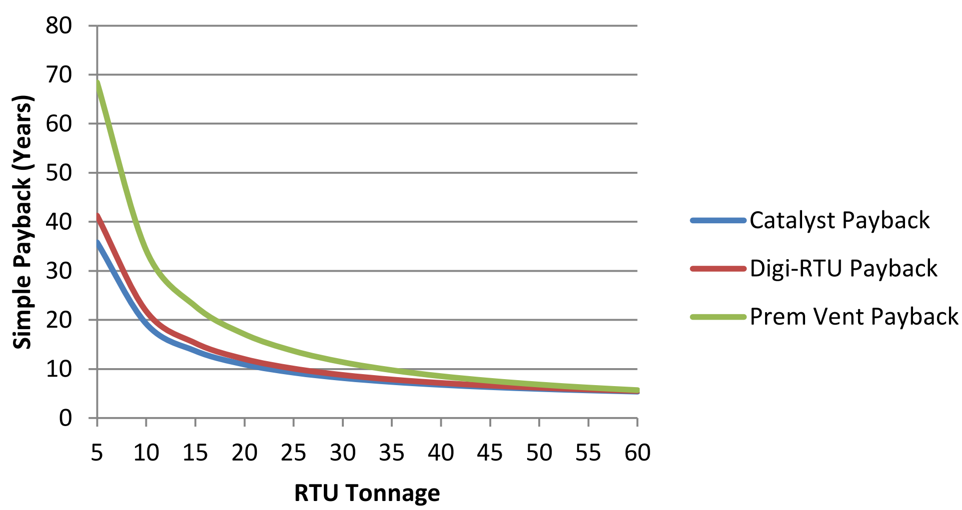
Since the RTUs that each technology were applied to had such a large variation in energy use per ton, the project team performed additional analysis examining how baseline energy use per ton impacts simple payback, assuming percent energy savings would remain consistent for each technology. Energy savings as a percentage of baseline energy use was multiplied by a range of baseline energy use scenarios roughly corresponding to the range observed in the study. Figure 20 shows estimated simple payback as a function of baseline energy use per ton of cooling capacity.

Figure 20. Payback as a Function of Baseline Energy Use Per Rated Ton of Cooling Capacity



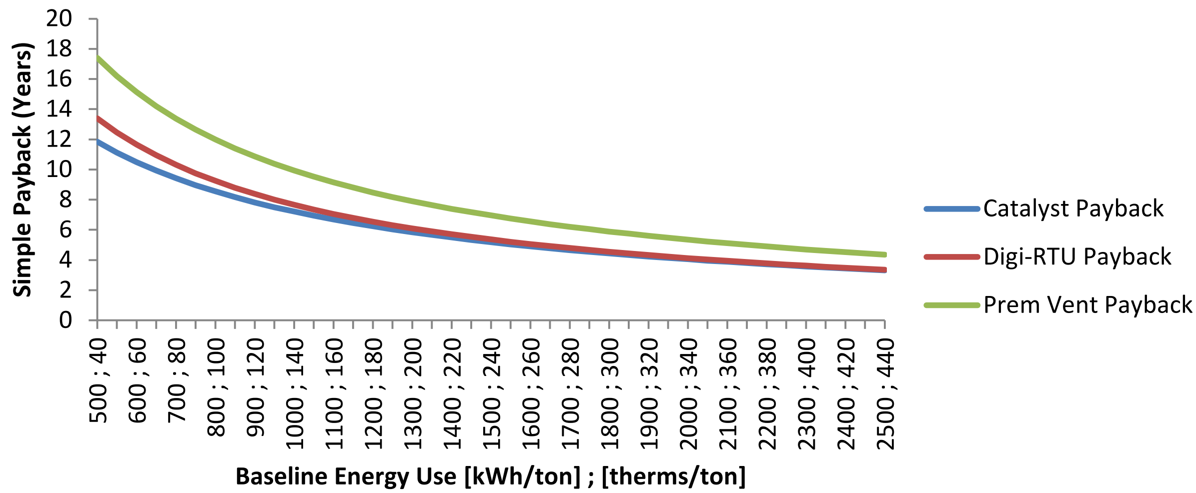
Recognizing that savings can generally be expected to increase with RTU tonnage, but that cost does not necessarily increase at the same rate, an analysis was performed to examine the impact of increasing the tonnage of a proposed installation on an RTU. This analysis assumed that the cost per RTU for a "Standard" site represents the cost to upgrade a 10 ton unit. For the Catalyst and Digi-RTU, which include a VFD, an additional $50 per ton of cooling capacity was assumed for units over 10 tons to account for increasing VFD costs for larger motors. Premium Ventilation costs were assumed to stay constant regardless of tonnage. Figure 21 shows payback as a function of RTU tonnage using these assumptions.

Figure 21. Payback as a Function of Rated Cooling Capacity



Adjusting the analysis of payback as a function of baseline energy use for estimated cost per ton for a 30 ton unit, yields paybacks approaching four years at the higher energy use intensities, as shown in Figure 22. These technologies have the potential to achieve cost-effective energy savings, depending on the actual application. Cost effectiveness is dependent on baseline energy use intensity (primarily kWh/ton) as well as RTU cooling capacity.

Figure 22. Payback as a Function of Baseline Use Per Ton for a 30 Ton Unit



6.7) Other Impacts

The analysis found that both basic and advanced controls maintained reasonable space temperatures and indoor air quality, based on CO2 concentration for the great majority of occupied hours. Our analysis indicates that the advanced controls did not have a significant positive or negative impact on thermal comfort or indoor air quality. Since most of the spaces in the study had relatively low occupant densities, these conclusions do not necessarily apply to spaces with higher occupant density, in which DCV features available for advanced controls may have a more definitive positive impact on indoor air quality.

As discussed in the energy savings results, the team observed interaction between units with advanced controls enabled and control. The results show that units that do not receive advanced controls use more energy when advanced controls are enabled. Based on the observed interaction, it is recommended that all units on a given building are upgraded in the course of an advanced controls project in order to minimize these potential negative impacts.

6.7.1) Space Temperature

The study collected space temperature data as an indicator of comfort and to compare the control points for both the advanced control and basic control modes of operation. Monthly site visits were made to all locations to collect independent stand-a-lone logger data which were installed at the thermostat location. The team documented checks on the setpoints for both the advanced control thermostat and basic control thermostat to track the changes that occurred over the course of the study. In general, these settings didn't change within a season, but did change between seasons. There was a transitional period between the full cooling and full heating season that caused occupants to adjust setpoint temperatures.

Data analysis was restricted to only weekday occupied periods and further refined to eliminate the potential for differences due to warm-up or cool-down conditions. The time periods for the data were centered around the middle of the day to assure that RTUs were at setpoints and cycling to maintain comfort in the space.

Appendix E provides outlier Box-and-whisker plots of space temperature for all RTUs. The plots show that for both the Catalyst and Digi-RTU controllers, the setpoints were maintained within acceptable ranges of error between controllers. However, this is not the case for the Premium Ventilation. The sequence for the Premium Ventilation control indicates that if occupants are not present in the space, heating and cooling setpoints will be adjusted to yield energy savings. Once the occupancy sensor detects movement, the setpoints will be restored to occupied levels. The differences that are displayed between the basic operation and the Premium Ventilation are expected and typical for spaces that are not occupied on a regular basis, such as meeting rooms.

6.7.2) Indoor Air Quality

With the large number of data points available for CO2 concentration, most cases displayed statistically significant differences between basic and advanced operation However, in practical terms these differences were generally deemed to be negligible, because CO2 concentration remained within levels used as the upper limit for demand controlled ventilation applications for the great majority of the time. ASHRAE 62.1 requires CO2 concentrations to be maintained at or below 700 ppm above outdoor air concentrations, which typically range between 300 to 500 ppm for DCV applications using CO2 sensors. Therefore, concentrations at or below 1000 to 1200 ppm are considered normal, requiring no additional ventilation beyond the minimum. The sites in the study had relatively low occupant densities, so it is not surprising that the advanced controls did not have a meaningful or consistent impact on CO2 concentration.

Appendix F provides outlier Box-and-whisker plots of CO2 concentrations for all RTUs at a given site, as well as for individual RTUs at each site.

6.7.3) Interaction with Control Units

Although the energy savings analysis indicates the control units generally used slightly more energy when other units in the building had advanced controls enabled, there was insufficient data to determine the cause. There was no correlation between the proximity of the control units to the advanced control units either. Some control units were serving the same occupied space as the advanced control units while others were controlling separate areas. The researchers hypothesized that advanced controls could cause temperature and/or pressure differentials between adjacent spaces (either physically connected or separate), causing units without controls to run more in order to make up for reduced conditioning from units with advanced controls. Additional research to the current data collection plan would be valuable, including the monitoring of space pressures, space temperatures, and occupancy. Until these interactions between RTUs are better understood, the team recommends installing advanced controls on all the RTUs in a building whenever possible.

7) KEY FINDINGS

7.1) Energy Savings

All technologies tested achieved statistically significant electric energy savings, but gas savings were a mix of negative or statistically insignificant. On a cost basis, gas savings were of a lower magnitude than electric savings. Savings across the study were highly variable, most likely because the baseline was defined as the as-found operation of the unit. Many units in the study were found operating with the supply fan cycling instead of operating continuously per ventilation code requirements. In addition, the study identified units with the minimum damper position set to 0 percent open[8]. This position may provide enough outside air ventilation due to leakage, but this study did not test leakage.

7.2) Cost Effectiveness

As applied in this study, the advanced controls did not achieve cost-effective energy savings. Installation on larger units, units with higher energy use intensities, or buildings with longer operating hours would improve cost effectiveness.

7.3) Occupant Comfort and Indoor Air Quality

Advanced controls did not meaningfully impact space temperature or indoor air quality. No occupants complained when units were operating as intended. These findings indicate that human comfort and indoor air quality remained consistent between basic and advanced operation.

7.4) Interaction with Control Group Units

The pilot observed a statistically significant interaction with units that did not receive advanced control retrofits. However, the interaction effect is small when compared to overall savings, and sites that included control groups maintained net positive savings. To avoid increased energy use on units without advanced controls, the study recommends upgrading all units on a given building. It is unclear what precisely caused the interaction. This may be an area of interest for future research.

7.5) Implications for CIP offerings

The pilot has verified that saving on the order of 30% electric energy is achievable by retrofitting existing 5-15 ton RTUs in Minnesota's heating dominated climate. A result that is consistent with other studies. That is much higher savings than has been achieved through traditional maintenance or tune-up programs.

But, the savings potential is very sensitive to the space-use type, operating schedule and internal loads. The pilot's experience with three products that used three different controls strategies revealed that, not surprisingly, the best controls strategy depends on the situation. By understanding each of the strategies strengths and weaknesses it is possible to optimize energy savings for a given situation. A classic case of one size does not fit all.

The pilot has also demonstrated that the cost of installing advanced RTU controls is very sensitive to product maturity, in a market where the designs of all the new products are rapidly evolving. The products that were tested have already been replaced with new and improved designs. Those improved designs have some additional performance features, although it's unlikely that energy savings will increase dramatically. More importantly the manufacturers have focused on simplifying installation and operations, which is critical to achieving wide spread market acceptance.

It is clear from the pilot's experience that local contractor support for advanced RTU controls products is critical to selling, installing and maintaining these products. These new products are complex relative to the traditional RTU controls contractors are used to working with. If the technologies are not installed and commissioned correctly, and maintained over time, the expected energy savings may not be achieved.

[8] The goal of the study was to document the savings that would be found in typical installations which included outside air dampers that had been set to zero as a result of comfort complains from the occupants

The electric energy savings potential of advanced RTU controls in dependent on the cooling season, which is relatively short in Minnesota. The current product costs are relatively expensive. The electric rates are relatively low in Minnesota. That results in simple paybacks for retrofit of advanced RTU controls that are typically greater than 5 years, and often 10-20 years. That is simply too long for most businesses. Due to economies of scale, paybacks are clearly shorter for larger RTUs and larger cooling loads.

Energy savings potential and utility electric rates are expected to be relatively stable. On the other hand, product maturity and product competition will result in significant reductions in both product costs and installation costs. Paybacks are expected to shorten, though probably not below 5 years for small to medium RTUs in Minnesota.

Understanding these issues is key to designing a successful CIP program that promotes the retrofit of existing RTUs with advanced controls. Based on the pilot experience we conclude that a CIP program that meets the benefit/cost requirements could be designed. To be successful, the CIP program must offer more than just rebates to buy down the initial cost. Design features include developing product selection guidance, estimated savings calculators and quality installation requirements.

Managing qualified installation contractors is probably the most critical issue for a CIP program. This is a new product, which has lots of implications. There is essentially no existing understanding of this type of product, no existing base of installed products and no existing base of contractors. At this time there are a limited number of small start-up like product manufacturers, which means rapidly evolving product designs and limited product distribution channels.

The situation is similar to the CFL products of the 1980's and to today's LED lighting products. The initial products were very expensive, product designs changed rapidly, and product quality was uneven. But, there were early adopters that jump started the market, utilities that promoted the products to increase awareness and market acceptance, the costs decline over time and the market stabilizes. The market for advanced RTU controls will likely follow a similar maturity path. It's important that the first CIP program design for advanced RTU controls address the early market issues of contractor/customer awareness, product quality and contractor training.

The first CIP program design must also be flexible enough to adapt to evolving product designs and installed costs. It is likely that the initial target participants for these products would have larger RTUs. But the expected product improvements would allow the CIP program to serve smaller RTUs cost effectively. Similarly, the space use type and operating schedule strongly impacts cost effectiveness. While the initial target would be heavily loaded RTUs, over time it's expected that most RTUs could participate.

Energy savings estimate dependencies include the controls strategy, RTU size, space-use type, operating schedules, internal load and for multiple RTUs, internal space-to-space air flow communications. A simple prescriptive rebate method would not work well for this product because there is too much variability is savings. A tool that accounts for the variety of RTU and operating situations should be developed to provide a systematic, standardized and yet customized way of calculating rebate amounts. For example, this tool could be a mobile app that would be available to contractors to collect key data, estimate rebates and submit the information to the CIP program administrator for approval.

Advanced RTU controls offer an opportunity to greatly improve the energy efficiency of the tens of thousands of existing RTUs in Minnesota. This pilot and other studies have shown that the controls strategies are technically sound and have field tested energy savings potential. The existing products early development cycle and associated costs limit their ability to quickly achieve large market penetration. A CIP program that offers market development services, contractor support services and rebates could accelerate the market acceptance of this new energy efficiency product. The CIP program design would be necessarily sophisticated, not just a simple prescriptive rebate. This CIP program has the potential to improve the energy efficiency of most of Minnesota's small to medium businesses.

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APPENDIX A - ADVANCE CONTROL DESCRIPTIONS

A.1) Premium Ventilation

Premium Ventilation package is a sequence of operation developed by PECI that can be installed on any number of thermostats with the necessary input and output control. CEE selected the KMC FlexStat thermostat for pilot project. A number of other programmable thermostats are able to perform the same function, but CEE's testing was based solely on the KMC platform.

A.1.1) Theory of Operation

The KMC FlexStat is an intelligent thermostat than can to be programed with custom code to enable any type of operation. KMC developed and optimized the Premium Ventilation code in partnership with PECI. The code has been tested in a number of mild weather test sites, but never in the relatively extreme climate of Minnesota. The custom code takes advantage of the onboard sensors and additional sensors to optimally control the RTU without the added expense of variable frequency drives. The KMC FlexStat has on board temperature, humidity, and occupancy sensors that are used as inputs to the control code. As with any thermostat, the space temperature is sensed and the RTU enabled or disabled to respond to loads within the space. The advanced nature of the FlexStat used the occupancy and humidity sensors to better control the space.

The existing occupancy sensor can be paired with additional occupancy sensors to give the FlexStat information on the utilization of the space. If no one is in the space, the FlexStat will adjust the setpoint up or down, depending on mode of operation to save energy. Similarly, the FlexStat will hold the HVAC unit in cooling for a longer period if the humidity setpoint is not met.

Additional sensors are also added to the KMC and utilized by the Premium Ventilation code to better control the economizer section of the RTU. As part of every Premium Ventilation installation, an outside air and discharge air sensor is added to better control the mix of outside and return air. These added sensors provide superior control over the standard packaged economizer controllers. The thermostat has the ability to monitor the local conditions indoor and out, and make better choices as to when to economize

Additional features of the KMC FlexStat include the ability to trend points on the thermostat and review parameters for optimal performance. The FlexStat also has the ability to be networked together and with additional software, assemble all thermostats into a building automation system capable of advance control and scheduling.

A.1.2) Installation Experience

Installing the Premium Ventilation requires several additional wire runs than the basic thermostat. If the Premium Ventilation were installed during original construction, the additional costs would be extra wire and sensors to control the RTU. The retrofit installation is much more involved, due to the wires that need to be installed in existing walls and roof penetrations. Installation in the retrofit is highly variable and cannot be accurately predicted across all building types and space uses.

A.1.3) Operation Issues

Compared to the other optimization packages in the pilot, the Premium Ventilation package is a combination of a manufactures' hardware with third party optimization routines which doesn't have a focused support channel. The FlexStat is supported by the manufacturer, KMC, but PECI developed the energy saving algorithms, and the KMC installs the code into the FlexStat. The modifications required as part of the deployment for this pilot came directly from KMC without consultation with PECI.

CEE experienced a number of issues with programming and the physical response of the Premium Ventilation. Staff discovered programming errors during the initial installation. Unknown to CEE, an alarm was set that disabled the operation of the thermostat whenever the discharge air sensor sensed a temperature below 40°F. This low temperature condition was experienced on several occasions when the thermostat was economizing during cooler weather. Consultation with the factory resolved this issue by lowering the alarm setpoint. The alarm was unnecessary, given that all the RTUs in the study used gas heating and there was no risk for internal freeze damage.

Another issue with the FlexStat was the room temperature measurement. Room sensors errors occurred during CEE's bench testing of the thermostats and were identified by bringing multiple thermostats in close proximity to each other. CEE observed a consistent three to four degree error on the FlexStat's space temperature reading. The FlexStat read consistently higher than the other temperature measurement devices. In a standard installation, the installer wouldn't have a second temperature reading device to compare, so this issue wasn't on the manufacturer's radar. CEE's typical installation is displayed in Figure 23.

Figure 23. Typical Installation, KMC on Left, Ventostat in Middle, Standard Thermostat on Right

CEE consulted again with the manufacturer about this observed space temperature error. In response, the manufacturer issued a calibration procedure that was required if there appeared to be an issue with the space temperature reading. This calibration procedure can be found on the internet under CO2 FlexStat Temperature Offset (document SB0412A).

A.1.4) Typical Installation Costs

Typical installation costs have been broken down between hardware and installation costs. The hardware costs are consistent across all installations. All installations require the KMC FlexStat, an outside air temperature sensor (10k Type III) and a discharge air temperature sensor (10K Type III). The majority of the installations also required an additional occupancy sensor so that the space conditioned by the RTU could be fully covered by the sensors to detect occupancy. There wasn't a limit on the number of additional occupancy sensors that could be added to cover the area, but in all cases, one additional sensor was sufficient to cover the space. The documented cost for the hardware for the pilot was $870 per RTU.

The installation costs for Premium Ventilation was a more difficult variable to estimate. Material costs were generally limited to the wire needed to connect the system. For a typical installation, the existing thermostat wire could be reused but an additional 8 conductor wire was needed to take control over the economizer and measurement temperatures both outside and discharge temperature. There was also the installation of the occupancy sensors which was highly variable based on the location of the sensor and the type of ceiling access. The typical installation would require the installation contractor to have on hand 8, 4 and 2 conductor wire in sufficient amounts to make runs between the thermostat location and the RTU on the roof.

The cost breakdown for the Premium Ventilation installation as documented for this pilot is given in Table 10. Two locations were documented, one with more than twice the number of installations.

Table 10. Actual Premium Ventilation Installation Costs

Location	# of RTUs	Labor Total	Material Total	Optimizer Cost	Site Total	Price per Unit
MDH	20	$32,279	$12,158	$17,400	$61,838	$3,091
NUR	7	$13,491	$6,735	$6,090	$26,317	$3,759
Totaled	27	$45,770	$18,894	$23,490	$88,155	$3,265

While the installation data collected for the pilot does represent a non-typical installation, there is a reasonable expectation that the costs for the typical installation should be close to what was experienced in this project. Using the hardware costs of $870 per RTU and the average installation costs from the two sites combined at $2,395, it cost $3,265 for each RTU in our study that had the Premium Ventilation package installed. CEE didn't have any additional sources to draw on for verification of the installation costs for the Premium Ventilation.

A.2) Digi-RTU

The Digi-RTU is the only optimization package that addresses the direct energy consumption of the refrigeration compressor, the largest component in an RTU.

A.2.1) Theory of Operation

The Digi-RTU optimizer uses a variable speed drive to reduce the output of both the supply fan and the compressor. The theory behind the operation is to match the output of the cooling and fan operation to that of the space. This is beneficial in almost all applications and even more so in the case of an over-sized RTU for the space. During the heating season, there is no modulation of the gas heating output but the supply fan is reduced during this operation to continue to yield electrical savings. The version this pilot tested limited the optimization to the speed control of the supply fan and compressors. The existing economizer control was retained and allowed to economize if the outside and return air conditions were appropriate for economizing.

A.2.2) Installation Experience

The installation experience for the Digi-RTU couldn't be considered typical. CEE's monitoring required installing a bypass to allow the RTU to operate in both basic and advanced modes. The bypass was a complicated component to install. Switching both high voltage three phase wires and low voltage control wires had to be configured to avoid causing issues with the RTUs' operation in either mode. Additionally, the size of the Digi-RTU required that for ease of installation a boom truck be contracted to lift the Digi-RTU cabinets to the roof deck. For small batch work, the cabinets could be carried up permanently installed steps to the roof but not recommended to carry up a ladder to the roofs edge. A picture of the typical Digi-RTU installed for the pilot project is displayed in Figure 24.

Figure 24. Typical Configuration of the Digi-RTU

A.2.3) Operation Issues

Over the course of the 16 month study, a few issues prevented the Digi-RTU from performing as expected. One of the primary goals of the pilot was to determine if all the optimization packages could work in the State of Minnesota. The Digi-RTU was the only package that yielded unanticipated results.

One of major areas of concern from the start of the project was the control of a single phase supply fan motor with a three phase variable frequency drive. The manufacturer assured CEE that there had been a limited amount of issues with the single phase fans. During the study period, four of the six units had failures of the single phase supply fan motors. In response to these failures, two separate solutions were implemented. The first was to remove the supply fan motor from speed control and operate it as it was originally configured. The compressor was the only component modulated after the modification. The second solution was to modify the control of the supply fan motor by allowing it to start only when the frequency drive was at full speed, and then modulating the speed down from that point. The reasoning behind the line frequency start was that the single phase motor didn't have sufficient torque at lower frequencies to initiate rotation; and if the motor didn't rotate due to the imposed voltage and current, the windings would fail. The final solution and recommendation from the manufacture was to keep the speed of the supply fan constant on any single phase supply fan motor systems. This sacrifices some savings by not controlling the indoor fan, but the typical single phase indoor fan motor is a fractional horsepower motor and does not use significant amounts of energy.

The other major issue with the operation of the Digi-RTU was its operation during cold weather. CEE experienced a wide spread failure of all Digi-RTU optimizers installed for the pilot during a cold weather period in Minnesota. The issue wasn't known to anyone at the time, but the operating range of the variable frequency drive used in the optimizer was 14 to 122 F (-10 to 50 C). Prior to the failure, the Digi-RTUs did function at lower outside ambient temperatures but the drive was energized and controlling a load, so staff assumed that the temperature inside the control cabinet didn't fall below the low limit threshold due to self-heating. The wide-spread failure occurred as a result of a switch between basic operation and the optimized operation over an extremely cold night. The VFD was temperature-soaked with low temperatures and couldn't provide operation that would generate self-heating.

The manufacturer's solution to the cold weather issue was to install a cabinet heater with a thermostat controller. The heaters ranged from 150 watt to 350 watt, depending on the volume of the enclosure. This solution was rejected by CEE given the relatively short window for collection of data and the fact that the cabinets were specifically designed to promote ventilation for cooling during summer operation. It was an unproven solution to a previously unknown issue. Additionally, the ability to measure the impact on savings was limited due to the delay in ordering and installation of the heaters. CEE chose to not operate the Digi-RTUs during the extreme cold weather, and continued the flip/flop testing after the cold months were over. It is assumed that the operation of the heaters would negatively affect the potential for savings for the Digi-RTU systems especially in the winter when the only savings that can be achieve by the Digi-RTU are fan savings.

A.2.4) Typical Installation Costs

Requirements for installing the Digi-RTU controller for the pilot work were a departure from what could be considered the typical Digi-RTU installation. The primary reason for this was that the bypass switch allowing the RTU to be operated in a basic mode of operation required a substantial amount of extra wiring on both the low voltage thermostat wires and the high voltage power wires for the compressor and indoor fan control. The bypass was critical to the flip/flop testing and proved essential for operating the RTUs in cold weather when the Digi-RTUs VFD failed to start.

The installation costs for the Digi-RTUs can again be broken down into hardware costs and installation costs. The hardware costs at the time of the pilot start were dependent on the size of the RTU with affects the size of the VFD required to control the unit. For the twelve RTUs outside of CEE's office the hardware costs are broken down in Table 11. Only the sites outside of CEE were used to document the installation costs. CEE's site was installed by the manufacturer as part of the preliminary work prior to the start of this pilot study.

Table 11. Actual Digi-RTU Installation Costs

Location	# of RTUs	Labor Total	Material Total	Optimizer Cost	Site Total	Price per Unit
SEI	9	$10,425	$9,163	$46,520	$66,119	$7,346
NOW	3	$7,749	$3,442	$15,510	$26,701	$8,900
Totaled	12	$18,174	$12,605	$62,040	$92,820	$7,735

A.3) Catalyst

A.3.1) Theory of Operation

The Catalyst controller is a VFD-based optimizer that integrates active control of the economizer, intelligent integration of the economizer with mechanical cooling and has demand based ventilation incorporated as the energy savings strategy. The VFD is only applied to the supply fan with additional sensors used to better control the mechanical cooling and economizer. The added sensors are return, supply, and outside air temperatures; and return air carbon dioxide. These sensors are used with energy savings algorithms to optimize the performance of the RTU.

A number of different options can be purchased for the Catalyst, with the most basic level being the installation of the Catalyst as a standalone system that controls the RTU. The Catalyst is installed between a standard thermostat and the RTU. It uses the information from the sensors and calls for heating or cooling from the thermostat to control the RTU. For example, if the thermostat calls for cooling and the Catalyst determines that it would be better to economize, it will not pass the signal to the RTU to activate mechanical cooling but it will open the economizer and "free" cool the space. The Catalyst will monitor the discharge air temperature and make more accurate decisions on when to bring on the mechanical cooling. All these control decisions are made at the controller and not visible to the occupant.

The highest level Catalyst incorporates a cellular connection that transfers data from the controller to the EIQ platform for web access to real time data. This option allows staff to remove the existing thermostat and replace it with a room temperature sensor that converts the standalone RTUs in to a building automation system capable of scheduling, adjusting setpoint, and detecting faults on all the RTUs at the site. CEE selected EIQ platform with a standard thermostat controlling as part of the pilot. Data accessibility was the most important factor in this decision, along with the ability to switch the Catalyst from energy savings mode to a standard mode of operation. This switch allowed for CEE's flip/flop testing protocol.

A.3.2) Installation Experience

Installation of the Catalyst controller was the most efficient of the three technologies studied. All the required hardware and miscellaneous parts are prepackaged in one box per RTU install. The installer is supplied with all the parts in one box and proceeds with the installation on the RTU. Our experience was somewhat biased by the presence of two factory representatives, but overall the factory made the installation as simple as possible. Further aiding installation, the boxes with required hardware were light enough that there was no need for a boom truck to move equipment to the roof. The boxes could be carried to the roof or pulled up with a rope.

CEE was able to install the six Catalyst controllers on a single roof in a day and a half with three technicians. Two of the technicians were factory representatives and the third was a first time installer being trained to perform the installations. The total man hours for this installation were 32 hours or 4 man days. A picture of a typical installation is displayed in Figure 25.

Figure 25. Picture of typical Catalyst Installation

A.3.3) Operation Issues

There were three issues with the operation of the Catalyst controller, which can be divided into installation and tuning issues. The installation issue was discovered by the parallel data collection from CEE's data logger. During the initial installation, the technician in training inadvertently landed the fan control signal on the second stage heating call and the second stage heating call on the fan control at the unit. Because the Catalyst makes all the decisions on fan control, it was never identified until CEE data for the monitoring system showed a constant call for second stage heating during the summer, just after the installation of the new controller. The wires were switched and the issue was resolved, but staff wouldn't have discovered this problem until the winter heating season, when the unit probably would have overheated the space on a call for heating.

There were two tuning issues that needed attention by CEE staff. The first was an over aggressive set back on supply fan flow during ventilation mode. The standard setting for the Catalyst was to reduce the fan speed to 40 percent during occupied time when there wasn't a call for heating or cooling. This allowed for air movement in the space and supplied outside air for ventilation purposes but did it at a much reduced volume and energy consumption level. This aggressive setback resulted in overheating of an interior-walled work space, which didn't have a thermostat, during summer conditions. The occupants requested more air to be delivered to that space which required the minimum fan speed to be elevated to 70 percent. The 70 percent speed solved the problem with comfort in the space.

The second tuning issue had involved the RTU's operation in heating mode. During extreme weather, the gas burner had a number of failures that couldn't be explained by the data collected on the unit. The service technicians dispatched to resolve the issue discovered that the RTUs burner control module was in fault due to overheating of the safety discharge air temperature sensor, integral to the control module. The fault could be tracked to a situation that if the thermostat was calling for second stage heating, the fan speed wasn't high enough to assure that the discharge air temperature would be below the high limit for the control module safety limit. The fault didn't occur every time, only after a prolonged period of burner operation in second stage heating. Initial setup of the Catalyst did account for temperature rise on the heat exchanger, but didn't synchronize the safety setting of the burner control module with the alarm temperature for the Catalyst. The solution was to lower the alarm temperature for the Catalyst so that the fan speed would increase as soon as the discharge temperature approached the fault temperature for the burner control sensor. While this was a relatively simple fix carried out by modification to the setpoints via the web interface, significant time lapsed between initial installation and identifying the problem. Finding the correct people to solve the problem could have been difficult without the support of the research staff on this pilot project.

A.3.4) Typical Installation Costs

Of the three optimization packages installed for this pilot, the Catalyst was the most developed for installation on the roof by a technician. As stated there was factory support for the install at our sites and the installation was limited to only 6 RTUs. The details of the installation are presented in Table 12.

Table 12. Actual Catalyst installation costs

Location	# of RTUs	Labor Total	Material Total	Optimizer Cost	Site Total	Price per Unit
MIN	6	$3,568	$1,000	$28,073	$32,641	$5,440

APPENDIX B – SITE DETAILS

B.1) CEE Site

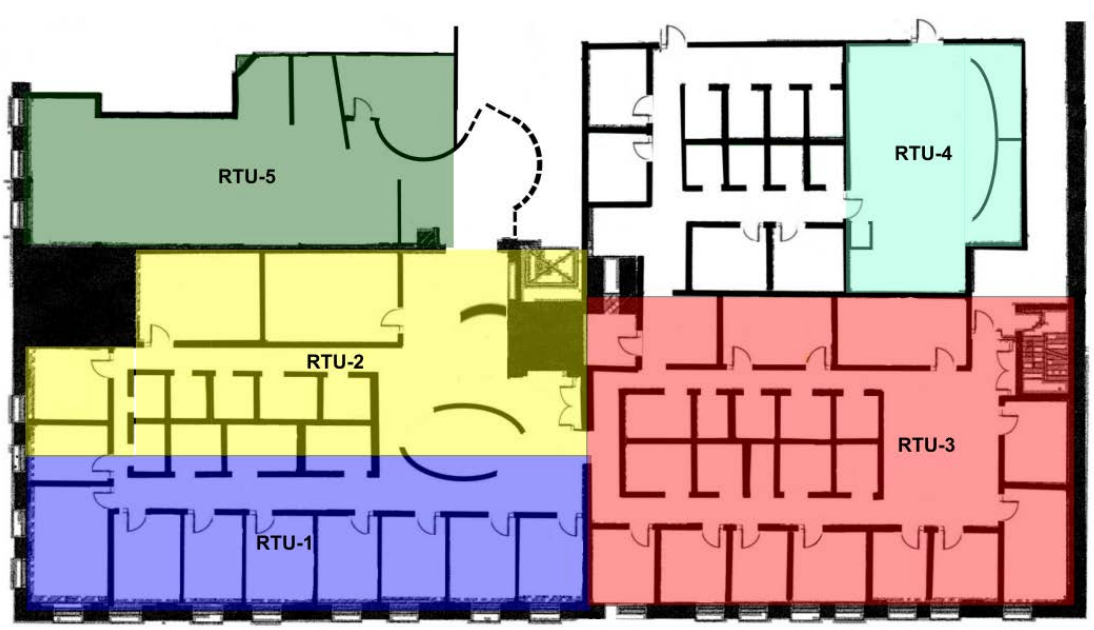
The first site that was tested was the office building for the Center for Energy of Environment. It is a 15,252 square foot office space on the fifth floor of a large warehouse building that is served by seven rooftop units. Two of these units had two optimization packages installed on them so they were counted twice in the overall number of RTUs tested in the study. A summary of the RTUs at CEE is displayed in Table 13.

The heat for units 1, 2, 6, and 7 is provided by hot water coils in the supply ductwork. These units were not included in the heating analysis. Units 1, 2, 3 and 5 have supplemental heat from hot water radiators on the perimeter of the space they serve. This affects the operation of these units during the heating season, as they show less heating than other units.

Table 13. Overview of RTUs at CEE Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Digi-RTU	Lennox	CHA16-513-5Y	Office, cubes	3.5
RTU-2	Digi-RTU	Lennox	CHA16-413-5Y	Office, cubes	3
RTU-3	Digi-RTU, KMC	Carrier	48HJE007-551HY	Office, cubes	6
RTU-4	Digi-RTU, KMC	Trane	YSC036E3RHAOUD0000000300	Small conference	3
RTU-5	KMC	Trane	4YCC3036A1064AA	Cubes	3
RTU-6	***None***	Carrier	50TFF007---501	Cubes	6
RTU-7	***None***	Carrier	50TJ-009---511--	Cubes	8.5

Figure 26. CEE Site Layout



B.1.1) Energy Use Characteristic

The energy use of CEE could not be evaluated. CEE's office is a small section of a larger five-story buildings. No data was available for whole building analysis.

B.2) NUR Site

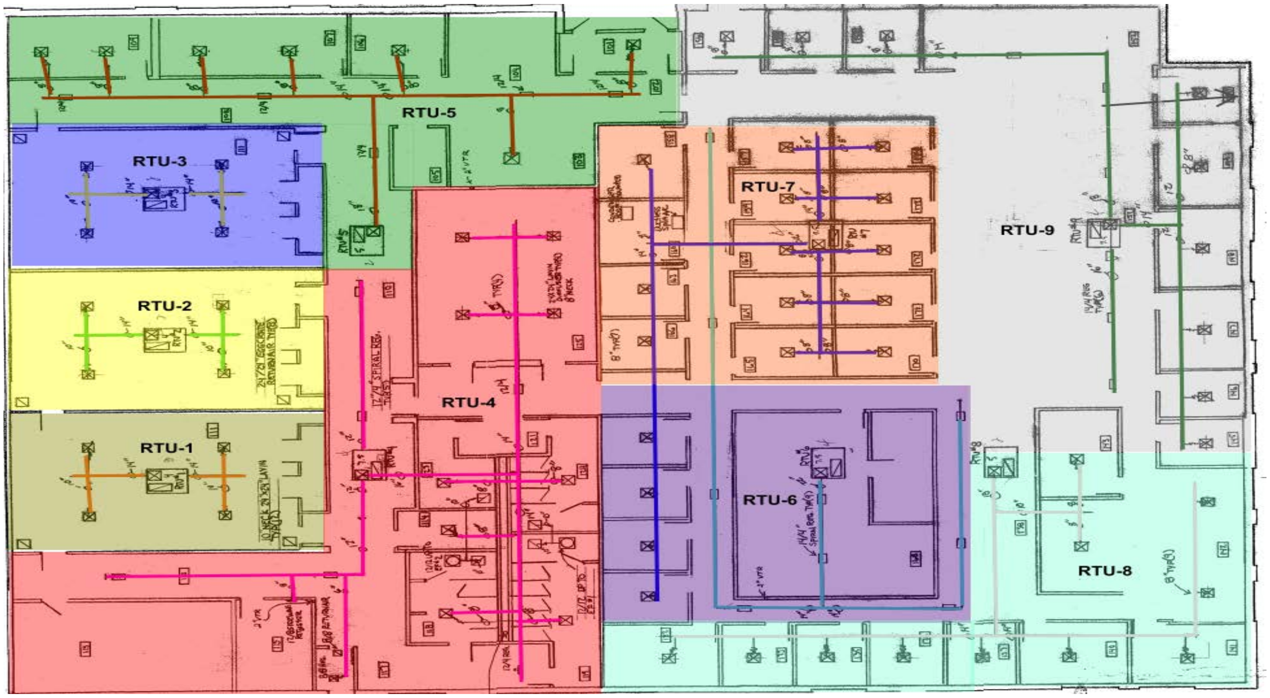
The NUR site is a 20,400 square foot single story office building with nine rooftop units. It is a mixture of large conference rooms, offices and cubes. The three conference rooms are served by units 1-3, and have moving partitions to separate each one. These are frequently moved to accommodate the size of the current meeting. Occupancy remains relatively stable throughout the site, with an increase only when there are conferences.

Rooftop units 4 and 9 were not retrofitted with an optimization package due to controllers installed by a third party mechanical contractor. RTU-4 had a controller on it that converted it to a two zone system. RTU-9 was converted to a two zone system variable volume system with a bypass in the supply ductwork that was used for volume control. Both modifications were such that the Premium Ventilation package would not be a good fit for the units, so units 4 and 9 were monitored as control units.

Table 14. Overview of RTUs at NUR Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Prem Vent	Carrier	48HJE005---651	Large conference	4
RTU-2	Prem Vent	Carrier	48HJE005---651	Large conference	4
RTU-3	Prem Vent	Carrier	48HJE005---651	Large conference	4
RTU-4	***None***	Carrier	48TME008-A-601	Hallway, Kitchen	7.5
RTU-5	Prem Vent	Carrier	48HJE006---641	Entry, Small conference	5
RTU-6	Prem Vent	Carrier	48TME008-A-601	Offices, cubes	7.5
RTU-7	Prem Vent	Carrier	48TME008-A-601	Offices, cubes	7.5
RTU-8	Prem Vent	Carrier	48HJE006--641	Offices, cubes	5
RTU-9	***None***	Carrier	48TME008-A-601	Offices, cubes	7.5

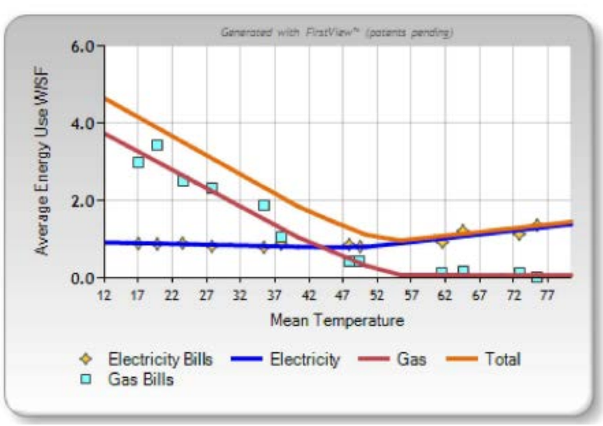
Figure 27. NUR site layout

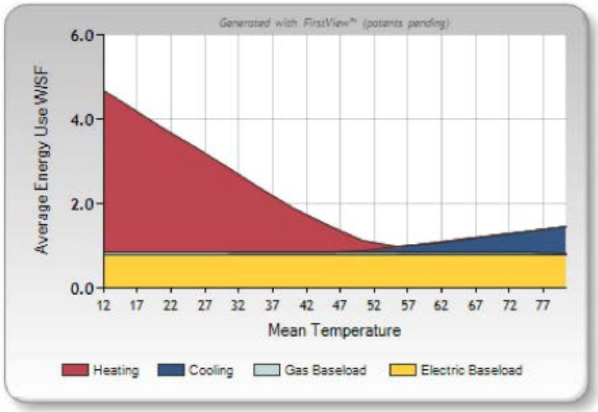


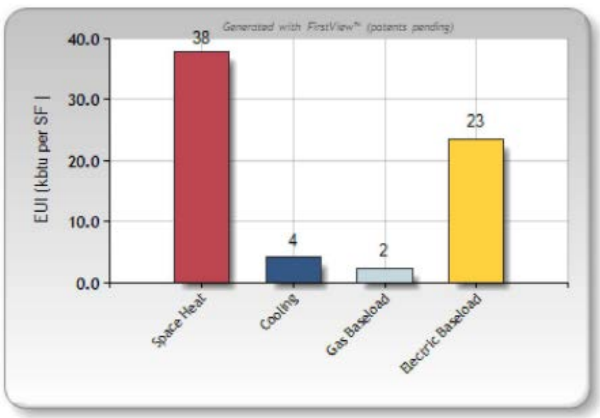
B.2.1) Energy Use Characteristic

The energy consumption at the NUR site was collected for a period of 2012 to 2013. The data was processed by FirstView software which disaggregates the consumption into base electric, base gas and then the temperature component of both electric and gas. Figure 28 displays the electric and gas use profile for the NUR site.

Figure 28. Energy use profile for NUR site







B.3) SEI Site

The SEI site is a 24,000 square foot office building that is served by nine rooftop units and shares a wall with the NUR site. It has two interior conference rooms and the rest offices and cubicles.

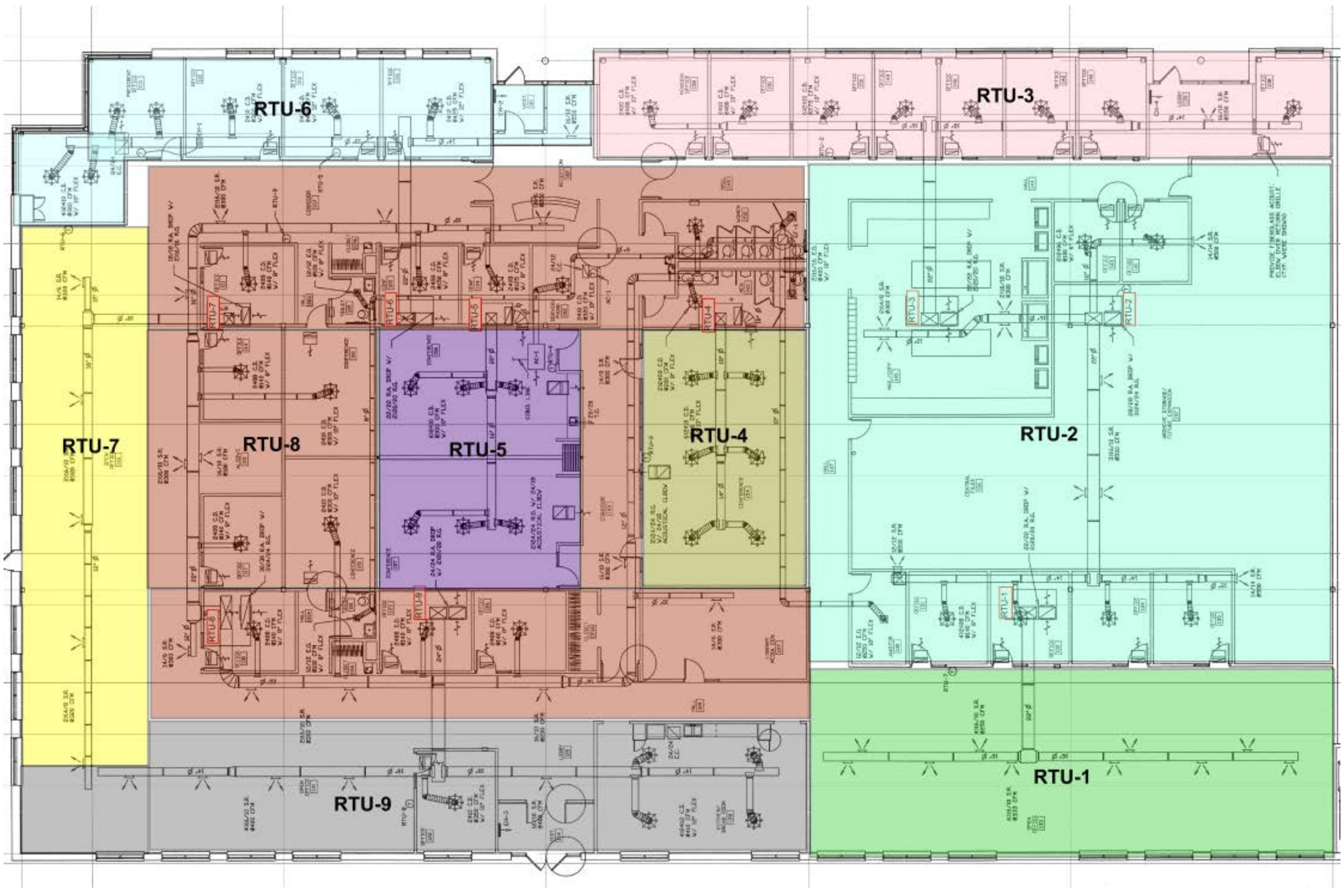
RTU-6 contains an electric resistive heating element located in the supply ductwork. Because the Digi-RTU reduces the airflow across this heater, there was a potential for the operation of the Digi-RTU to cause damage to heater. For this reason, RTU-6 was not run under advanced control during heating season.

Table 15. Overview of RTUs at SEI Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Digi-RTU	Lennox	TGA090S2BM1G	Offices, cubes	7.5
RTU-2	Digi-RTU	Lennox	TGA150S2BH1G	Storage	12.5
RTU-3	Digi-RTU	Lennox	TGA090S2BM1G	Offices, cubes	7.5
RTU-4	Digi-RTU	Lennox	TGA048B2DM1G	Medium conference	4
RTU-5	Digi-RTU	Lennox	TGA060B2DH1G	Medium conference	5
RTU-6	Digi-RTU	Lennox	TGA090S2BM1G	Offices	7.5
RTU-7	Digi-RTU	Lennox	TGA048B2DM1G	Cubes	4
RTU-8	Digi-RTU	Lennox	TGA180S2BM1G	Hallway, offices	15

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-9	Digi-RTU	Lennox	TGA120S2BH1G	Offices, cubes	10

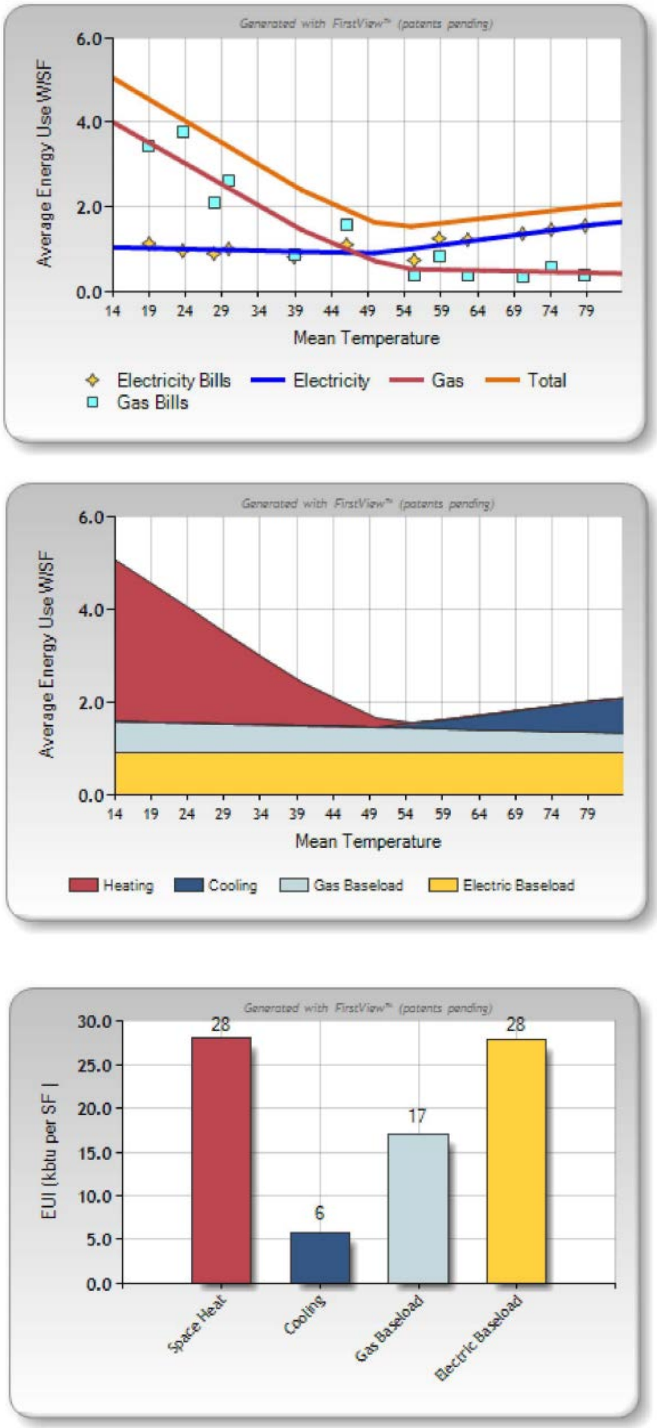
Figure 29. SEI Site Layout



B.3.1) Energy Use Characteristic

The FirstView graphs for the monthly utility consumption for the SEI site are displayed below.

Figure 30. Energy use profile for SEI site



B.4) MDH Site

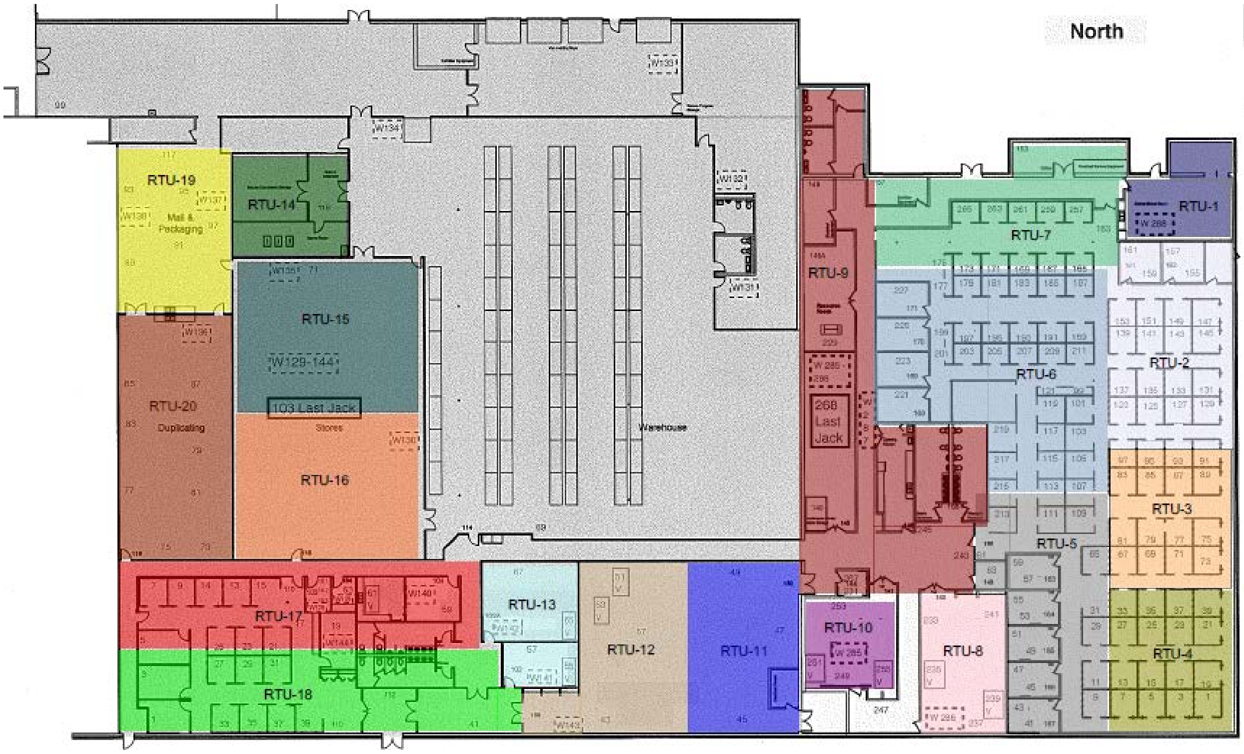
The MDH site is a 64,000 square foot single-story office building with 20 rooftop units. It is the largest building in the project and has a wide variety of space types including multiple conference rooms, Warehouse areas, light manufacturing, cubicles, shipping and receiving, and offices.

The data monitoring period was cut short because MDH elected not to renew their lease. Data was collected at the site as long as possible, with CEE in close contact with the property manager to get feedback as to when areas were vacated. The space served by units 1-10 was unoccupied as of 1/1/13, and the building was completely unoccupied by 3/27/13.

Table 16. Overview of RTUs at MDH Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Prem Vent	Lennox	LGA088H1G	Kitchen	7.5
RTU-2	Prem Vent	Lennox	GCS16-036-90-1G	Offices, cubes	3
RTU-3	Prem Vent	Lennox	GCS16-036-90-2G	Cubes	3
RTU-4	Prem Vent	Lennox	GCS16-036-90-1G	Cubes	3
RTU-5	Prem Vent	Lennox	LGA120SH1G	Offices, cubes	10
RTU-6	Prem Vent	Lennox	LGA120SH1G	Offices, cubes	10
RTU-7	Prem Vent	Lennox	LGA120SH1G	Cubes, hallway	10
RTU-8	Prem Vent	Lennox	LGA088SH1G	Medium conference	7.5
RTU-9	Prem Vent	Lennox	LGA088SH1G	Hallway, Kitchen	7.5
RTU-10	Prem Vent	Lennox	GCS24-813-130-2G	Medium conference	15
RTU-11	Prem Vent	Lennox	LGA150SH2G	Large conference	12.5
RTU-12	Prem Vent	Lennox	LGA150SH2G	Large conference	12.5
RTU-13	Prem Vent	Lennox	GSC24-813-130-2G	Small conference	15
RTU-14	Prem Vent	Lennox	GCS20-060-120-1G	Server room	5
RTU-15	Prem Vent	Lennox	GCS24-813-130-2G	Storage	15
RTU-16	Prem Vent	Lennox	GCS24-813-130-2G	Storage	15
RTU-17	Prem Vent	Lennox	LGA120SH1G	Offices, cubes	10
RTU-18	Prem Vent	Lennox	GCS24-953-200-1G	Offices, cubes	8
RTU-19	Prem Vent	Lennox	GCS20-060-120-1G	Mail/Packaging	5
RTU-20	Prem Vent	Lennox	GSC24-953-200-1G	Printing	8

Figure 31. MDH site layout



B.4.1) Energy Use Characteristic

Historic energy use could not be collected at the MDH site. No energy use characteristics could be generated.

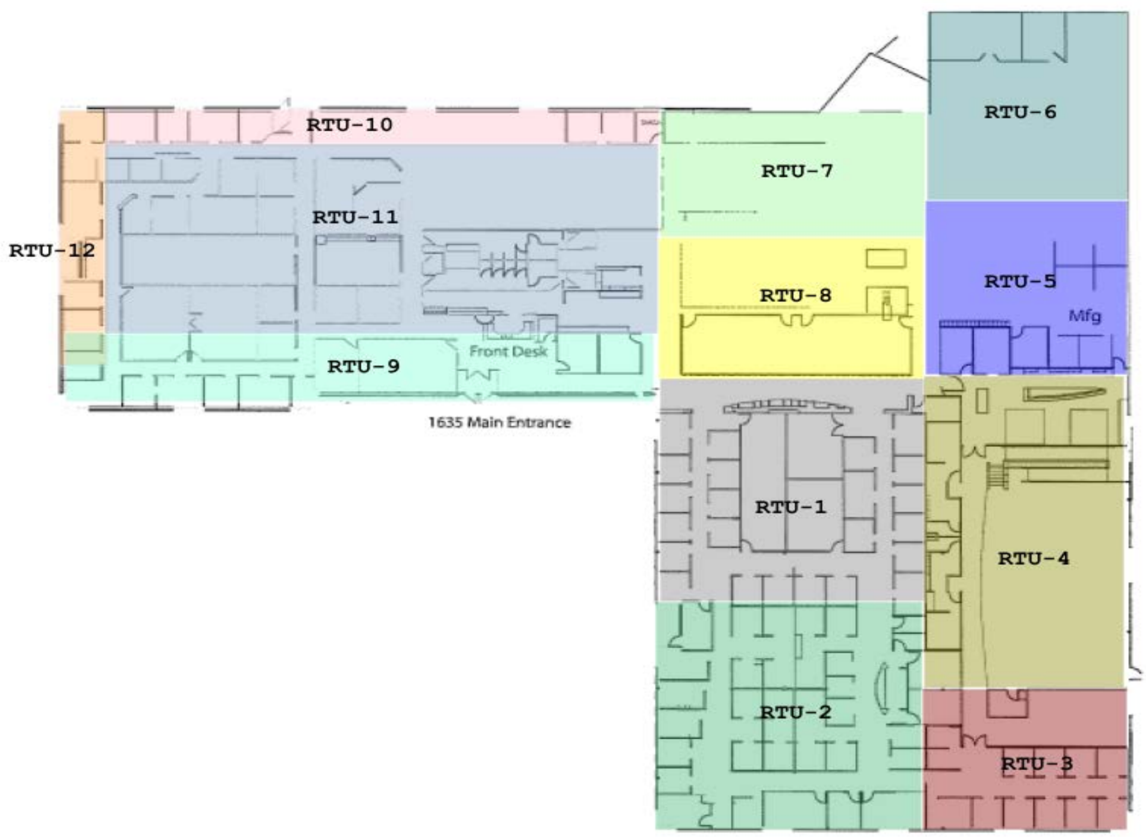
B.5) MIN Site

The MIN site is a 46,000 square foot office building that is served by 12 rooftop units. The space is a mixture of manufacturing, shipping and receiving, offices and cubicles.

Table 17. Overview of RTUs at MIN Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Catalyst	Bryant	580FEV120224AB	Offices, cubes	10
RTU-2	Catalyst	Bryant	580FEV150224AB	Offices, cubes	12.5
RTU-3	Catalyst	Bryant	580FEV150224AB	Offices, cubes	12.5
RTU-4	Catalyst	Bryant	580FEV120224AB	Kitchen, gym	10
RTU-5	Catalyst	Bryant	580FEV120224AB	Manufacturing	10
RTU-6	Catalyst	Bryant	580FEV150224AB	Manufacturing	12.5
RTU-7	None	Trane	YCD048C3HBBF	Storage	4
RTU-8	None	Trane	YCD150C3HABB	Manufacturing	12.5
RTU-9	None	Trane	YCD120C3M0AC	Entry, small conference	10
RTU-10	None	Trane	YCD060C3HBBF	Offices, cubes	5
RTU-11	None	Trane	YCD150C3HABB	Manufacturing	12.5
RTU-12	None	Trane	YCD075C3H0BE	Offices, cubes	6

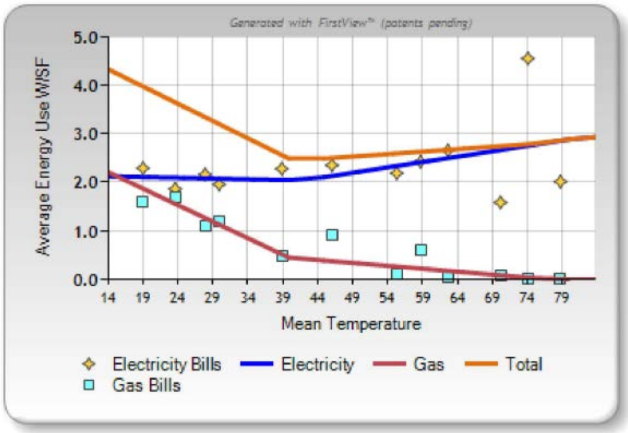
Figure 32. MIN Site Layout

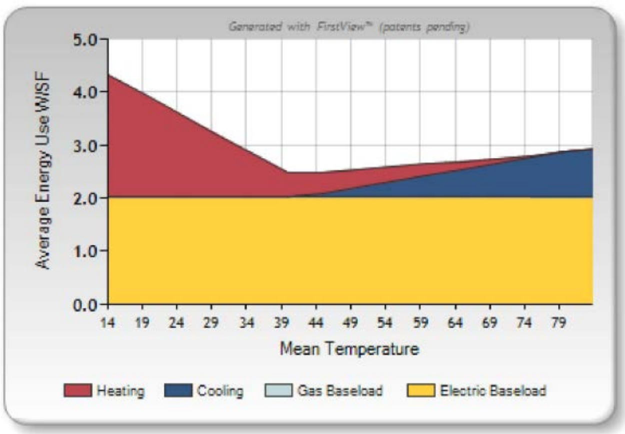


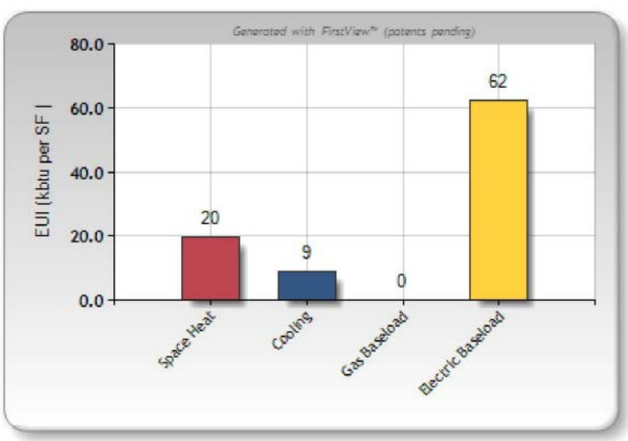
B.5.1) Energy Use Characteristic

The FirstView graphs for the monthly utility consumption for the MIN site are displayed below.

Figure 33. Energy use profile for MIN site







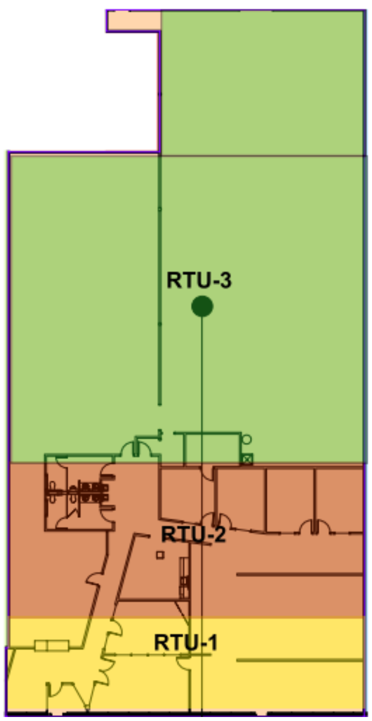
B.6) NOW Site

The Now site is a 16,000 square foot office building that is served by three units. Roughly half of the space is offices and cubicles, while the other half is used for manufacturing and storage. The space is part of a large office building and has two common walls with other businesses on either side.

Table 18. Overview of RTUs at NOW site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RTU-1	Digi-RTU	Trane	YSC048A4EHA2UD00000000600	Offices, cubes	4
RTU-2	Digi-RTU	Trane	YSC102A4EHA2UD00000000600	Offices, cubes	8.5
RTU-3	Digi-RTU	Trane	YSC090A4EHA30D00000000600	Manufacturing, storage	7.5

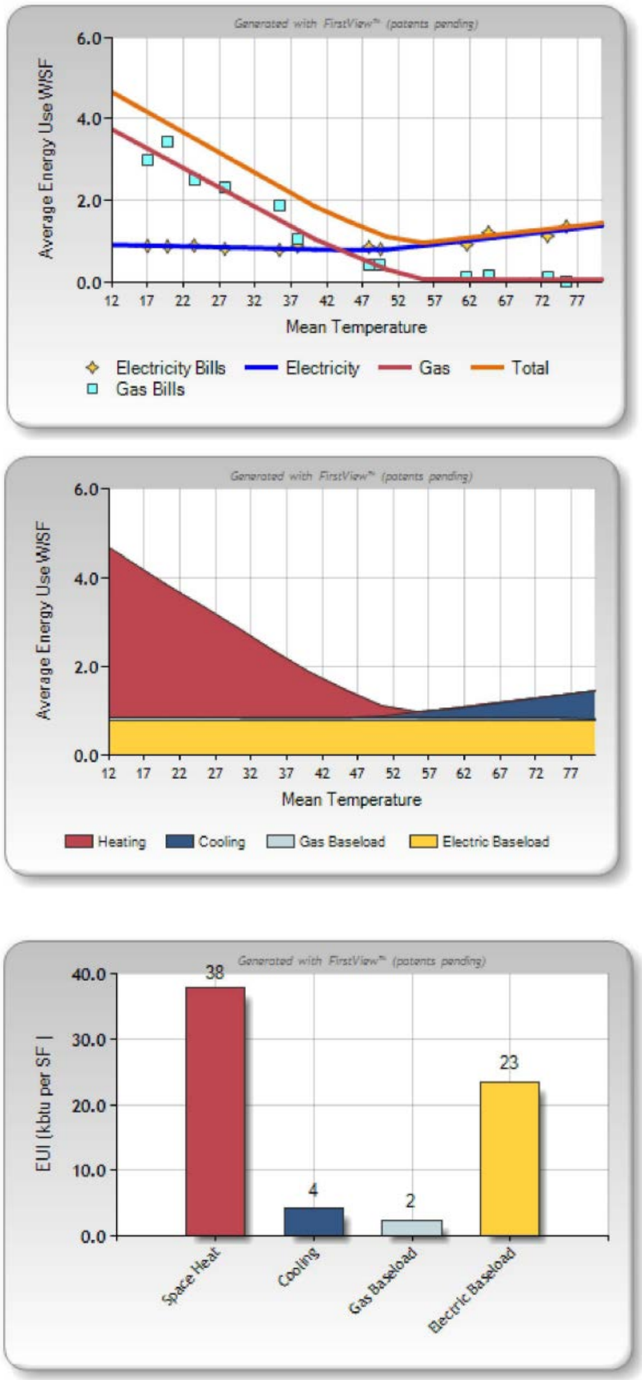
Figure 34. Site NOW Layout



B.6.1) Energy Use Characteristic

The FirstView graphs for the monthly utility consumption for the NOW site are displayed below.

Figure 35. Energy use profile for NOW site



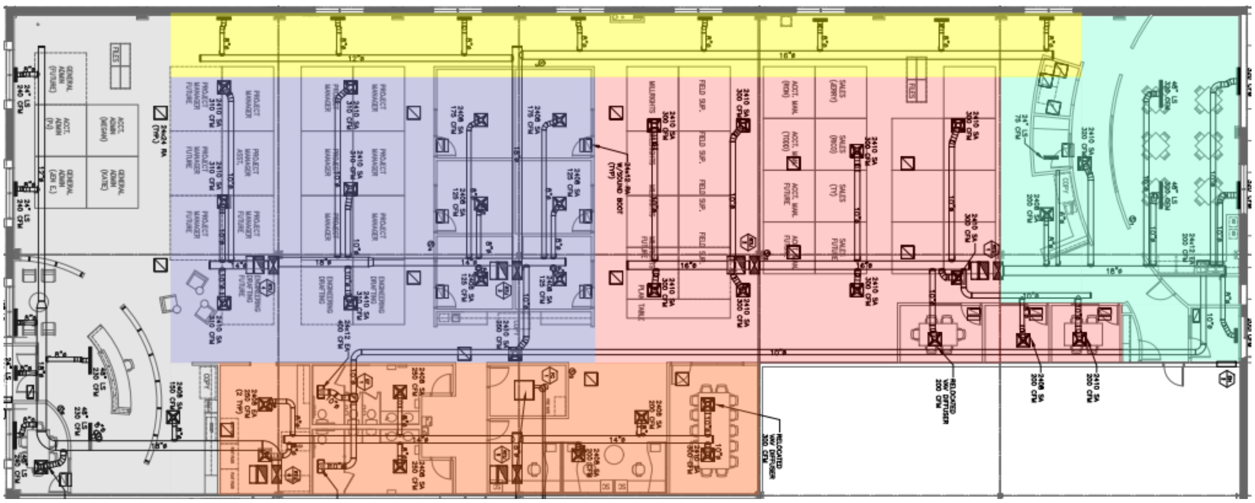
B.7) YAL Site (added site)

The YAL site was added very late in the project and was only included to provide additional performance points for the Catalyst controller. The YAL site is a 45,000 ft2 single story office building primarily used for office work. There are a number of enclosed offices on the perimeter of the conditioned space with cubical in the center. The office does have some conference room space that the occupants use for internal meetings.

Table 19. Overview of RTUs at YAL Site

Unit	Optimization Package	Manufacturer	Model #	Space Type	Tonnage
RHC-1	Catalyst	Trane	YHC060E4RMA0YD2A1C1B100A3	Lunch room	5
RHC-2	Catalyst	Trane	YHC092E4RMA0AD0A1C1B100A3	Office, interior	7.5
RHC-3	Catalyst	Trane	YHC060E4RMA0YD2A1C1B100A3	Office, exterior	5
RHC-4	Catalyst	Trane	YHC092E4RMA0AD0A1C1B100A3	Office, interior	7.5
RHC-5	Catalyst	Trane	YHC060E4RMA0YD2A1C1B100A3	Reception	5
RHC-6	Catalyst	Trane	YHC060E4RMA0YD2A1C1B100A3	Office, interior	5

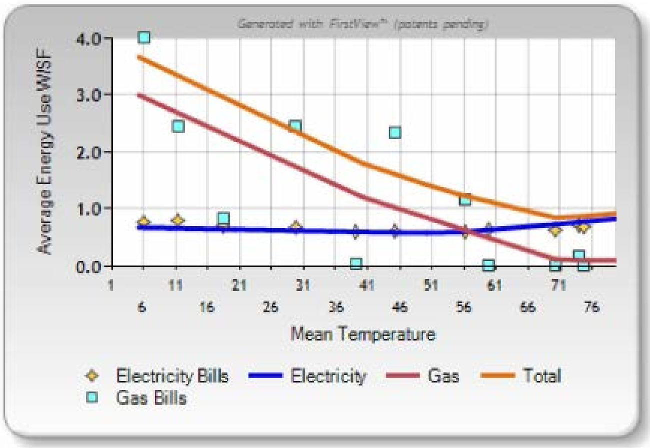
Figure 36. Site YAL Layout

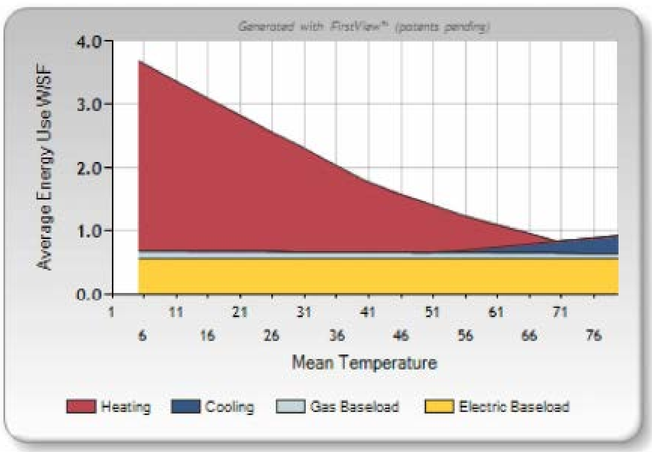


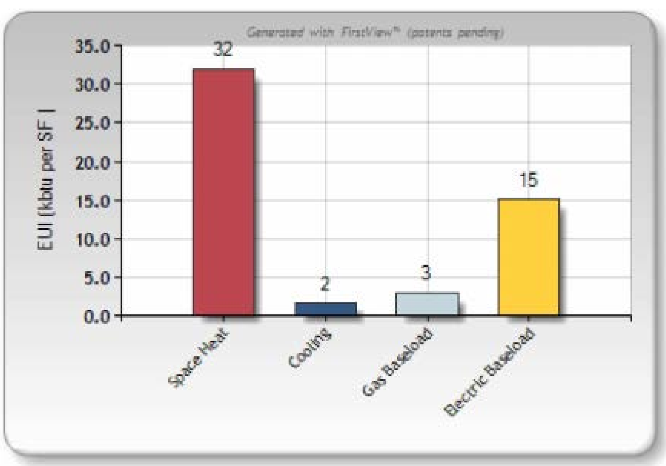
B.7.1) Energy Use Characteristic

The FirstView graphs for the monthly utility consumption for the YAL site are displayed below.

Figure 37. Energy use profile for YAL site







APPENDIX C – LIST OF RTUS MODELS ELIMINATED FROM ANALYSIS

List of RTU's that were eliminated from the analysis and reason for exclusion

Excluded Site_Unit	Fuel Type	Reason for Exclusion
cee_rtu_4	Gas	CEE site has hot water heat, non-characteristic gas use
cee_rtu_4	Gas	CEE site has hot water heat, non-characteristic gas use
cee_rtu_6	Electric	Not a valid control unit due to potential interference from other experiments
cee_rtu_6	Gas	CEE site has hot water heat, non-characteristic gas use
cee_rtu_7	Gas	CEE site has hot water heat, non-characteristic gas use
cee_rtu_7	Electric	Not a valid control unit due to potential interference from other experiments
mdh_rtu_10	Electric	Did not display characteristic temperature dependence, acceptable regression not achieved
min_rtu_11	Gas	Not enough gas use data to produce reliable savings estimate
min_rtu_7	Gas	Not enough gas use data to produce reliable savings estimate
min_rtu_7	Electric	Suspected issue with baseline cooling, no cooling energy use in baseline
min_rtu_8	Gas	Not enough gas use data to produce reliable savings estimate
min_rtu_9	Electric	Did not display characteristic temperature dependence, acceptable regression not achieved
nur_rtu_4	Electric	Did not display characteristic temperature dependence, acceptable regression not achieved
sei_rtu_4	Gas	Not enough gas use data to produce reliable savings estimate
sei_rtu_4	Electric	Not enough electric use data to produce reliable savings estimate
sei_rtu_5	Gas	Not enough gas use data to produce reliable savings estimate
sei_rtu_group_6_thru_9	Electric	Not enough electric use data to produce reliable savings estimate
sei_rtu_group_6_thru_9	Gas	Not enough gas use data to produce reliable savings estimate

APPENDIX D – INDIVIDUAL SAVINGS BY RTU

Figure 38. Electric Energy Savings by RTU

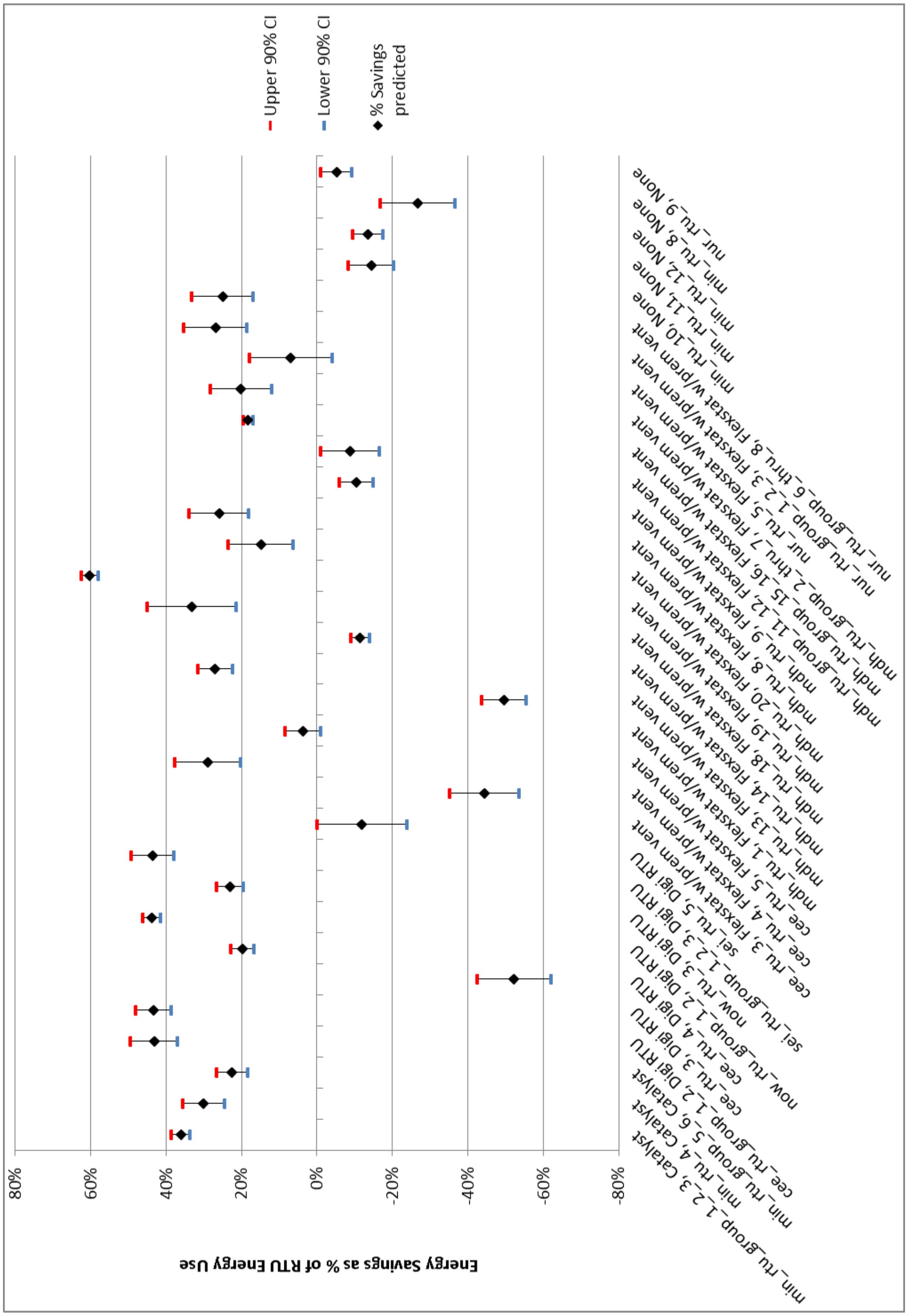


Figure 39. Gas Energy Savings by RTU

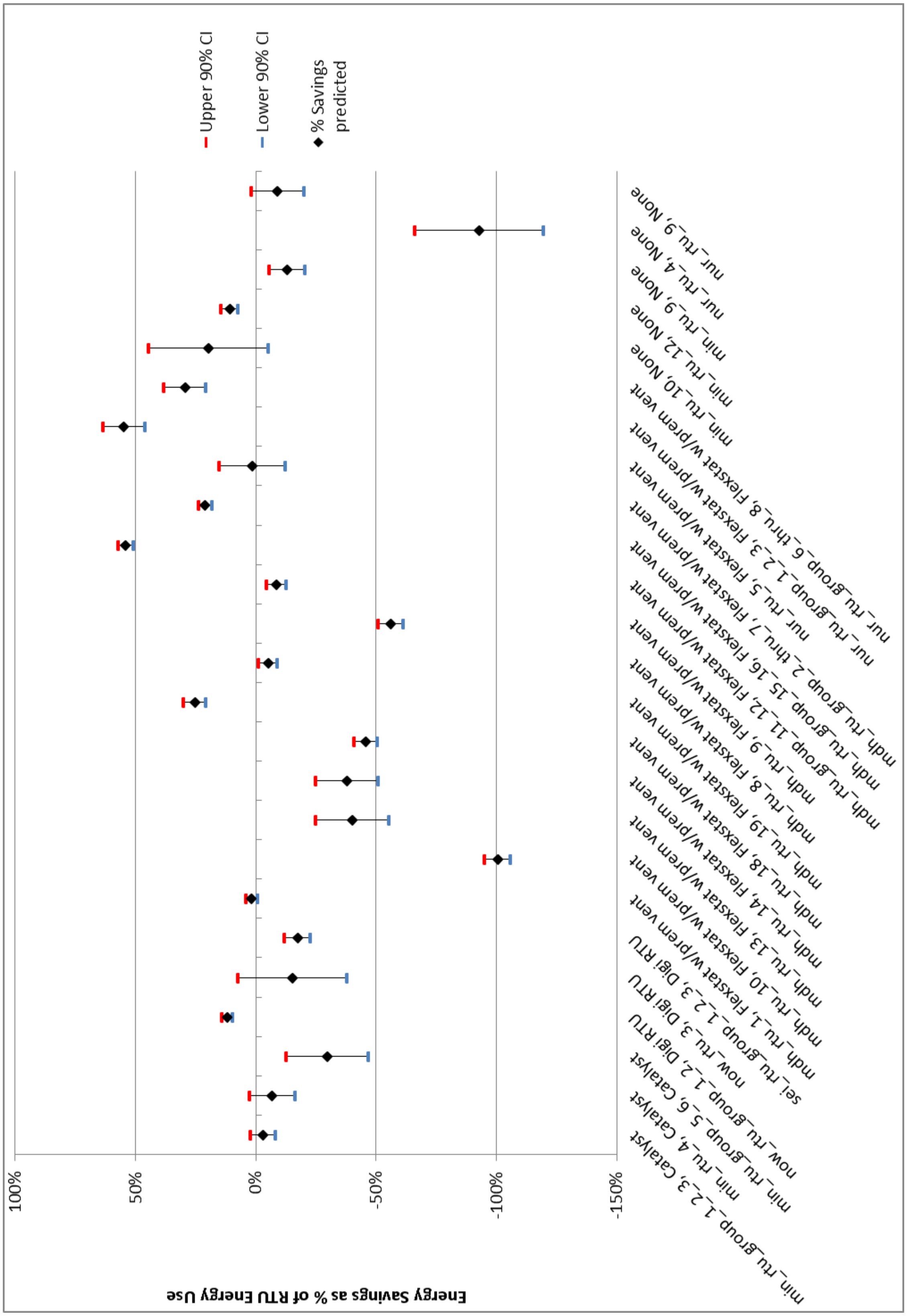


Table 20 and Table 21 provide absolute values for normalized annual energy use and savings, and the confidence interval for the savings estimates.

Table 20. Electric Energy Use and Savings Results with 90 percent Confidence Limits

Electric Energy Data kWh	Normalized Use Pre ("Basic")	Normalized Use Post ("Advanced")	Normalized Savings Estimate	Lower 90% Confidence Limit	Upper 90% Confidence Limit
min_rtu_group_1_2_3, Catalyst	44,718	28,634	16,084	14,976	17,192
min_rtu_4, Catalyst	18,422	12,899	5,523	4,507	6,539
min_rtu_group_5_6, Catalyst	56,944	44,163	12,780	10,458	15,103
cee_rtu_group_1_2, Digi RTU	8,864	5,044	3,819	3,270	4,369
cee_rtu_3, Digi RTU	5,949	3,376	2,573	2,295	2,852
cee_rtu_4, Digi RTU	1,190	1,814	(623)	(740)	(506)
now_rtu_group_1_2, Digi RTU	13,726	11,021	2,705	2,290	3,121
now_rtu_3, Digi RTU	5,081	2,861	2,220	2,100	2,340
sei_rtu_group_1_2_3, Digi RTU	18,629	14,348	4,281	3,630	4,932
sei_rtu_5, Digi RTU	5,444	3,075	2,369	2,058	2,680
cee_rtu_3, Prem vent	5,949	6,662	(712)	(1,418)	(6)
cee_rtu_4, Prem vent	1,190	1,720	(530)	(640)	(420)
cee_rtu_5, Prem vent	2,794	1,988	806	563	1,050
mdh_rtu_1, Prem vent	2,586	2,493	93	(29)	215
mdh_rtu_13, Prem vent	3,543	5,301	(1,758)	(1,967)	(1,548)
mdh_rtu_14, Prem vent	9,923	7,251	2,671	2,220	3,123
mdh_rtu_18, Prem vent	6,620	7,384	(764)	(929)	(599)
mdh_rtu_19, Prem vent	1,222	817	404	260	548
mdh_rtu_20, Prem vent	10,931	4,358	6,573	6,328	6,817
mdh_rtu_8, Prem vent	3,025	2,577	448	187	708
mdh_rtu_9, Prem vent	8,937	6,623	2,314	1,604	3,024
mdh_rtu_group_11_12, Prem vent	10,118	11,179	(1,061)	(1,508)	(614)
mdh_rtu_group_15_16, Prem vent	4,078	4,442	(364)	(683)	(45)
mdh_rtu_group_2_thru_7, Prem vent	16,413	13,426	2,987	2,775	3,199
nur_rtu_5, Prem vent	6,409	5,122	1,288	769	1,807
nur_rtu_group_1_2_3, Prem vent	3,711	3,456	255	(151)	662
nur_rtu_group_6_thru_8, Prem vent	14,915	10,909	4,005	2,767	5,244
min_rtu_10, None	13,641	10,243	3,398	2,290	4,506

Electric Energy Data kWh	Normalized Use Pre ("Basic")	Normalized Use Post ("Advanced")	Normalized Savings Estimate	Lower 90% Confidence Limit	Upper 90% Confidence Limit
min_rtu_11, None	21,238	24,301	(3,063)	(4,344)	(1,782)
min_rtu_12, None	4,887	5,550	(663)	(862)	(465)
min_rtu_8, None	18,565	23,536	(4,971)	(6,797)	(3,146)
nur_rtu_9, None	10,284	10,820	(537)	(955)	(118)

Table 21. Gas Energy Use and Savings Results with 90 percent Confidence Limits

Gas Energy Data Therms	Normalized Use Pre ("Basic")	Normalized Use Post ("Advanced")	Normalized Savings Estimate	Lower 90% Confidence Limit	Upper 90% Confidence Limit
min_rtu_group_1_2_3, Catalyst	3,137	3,236	(99)	(259)	61
min_rtu_4, Catalyst	1,333	1,427	(93)	(220)	33
min_rtu_group_5_6, Catalyst	1,273	1,653	(380)	(597)	(163)
now_rtu_group_1_2, Digi RTU	2,128	1,879	249	200	298
now_rtu_3, Digi RTU	107	124	(16)	(41)	8
sei_rtu_group_1_2_3, Digi RTU	4,082	4,796	(714)	(932)	(496)
mdh_rtu_1, Prem vent	1,109	1,092	18	(8)	44
mdh_rtu_10, Prem vent	318	637	(319)	(336)	(303)
mdh_rtu_13, Prem vent	165	231	(66)	(92)	(41)
mdh_rtu_14, Prem vent	320	441	(121)	(163)	(80)
mdh_rtu_18, Prem vent	1,604	2,339	(735)	(814)	(655)
mdh_rtu_19, Prem vent	592	442	150	123	176
mdh_rtu_20, Prem vent	7	75	(68)	(80)	(56)
mdh_rtu_8, Prem vent	614	646	(32)	(55)	(9)
mdh_rtu_9, Prem vent	4,887	7,628	(2,742)	(2,994)	(2,489)
mdh_rtu_group_11_12, Prem vent	1,997	2,169	(172)	(254)	(89)
mdh_rtu_group_15_16, Prem vent	1,867	860	1,008	948	1,067
mdh_rtu_group_2_thru_7, Prem vent	4,693	3,713	980	852	1,107
nur_rtu_5, Prem vent	1,261	1,243	17	(155)	190
nur_rtu_group_1_2_3, Prem vent	597	271	326	275	378
nur_rtu_group_6_thru_8, Prem vent	2,079	1,471	608	426	790
min_rtu_10, None	42	34	8	(2)	19
min_rtu_12, None	3,066	2,735	331	217	444
min_rtu_9, None	168	190	(22)	(35)	(9)
nur_rtu_4, None	629	1,214	(585)	(753)	(417)
nur_rtu_9, None	1,454	1,588	(134)	(294)	26

APPENDIX E – SPACE TEMPERATURE

Figure 40. Space temperature box and whisker plots for CEE site

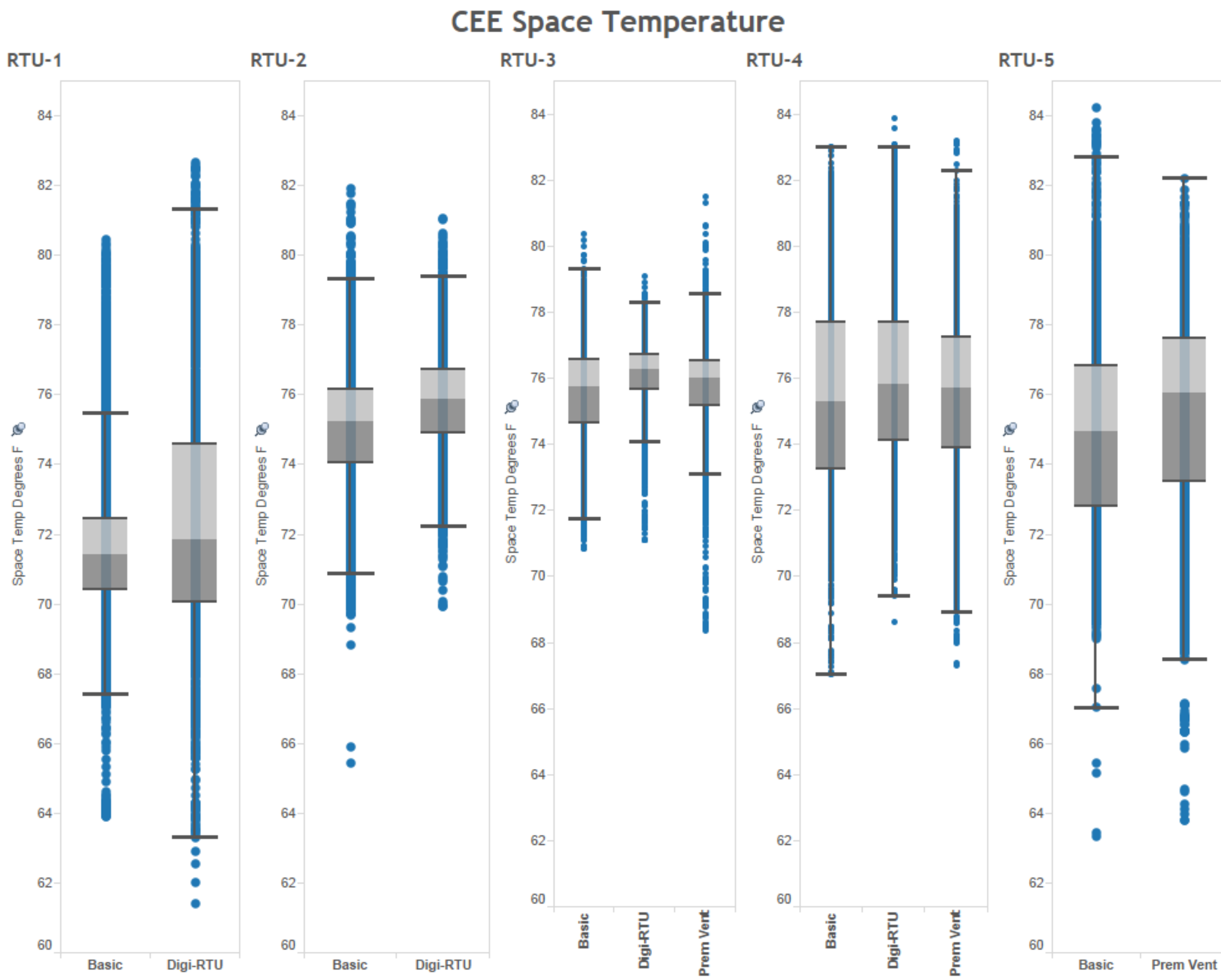


Figure 41. Space temperature box and whisker plots for MDH site (RTUs 1-5)

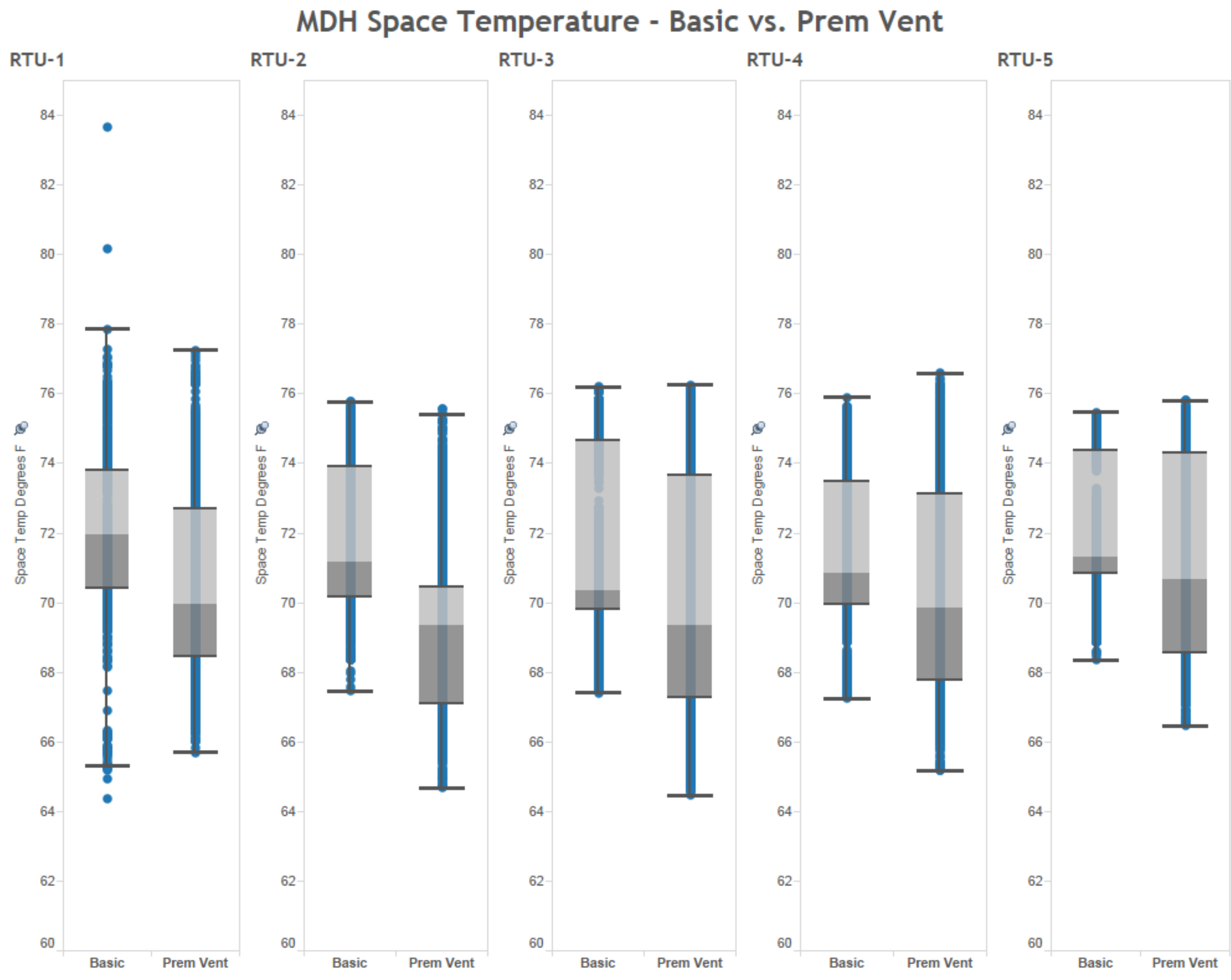


Figure 42. Space temperature box and whisker plots for MDH site (RTUs 6-10)

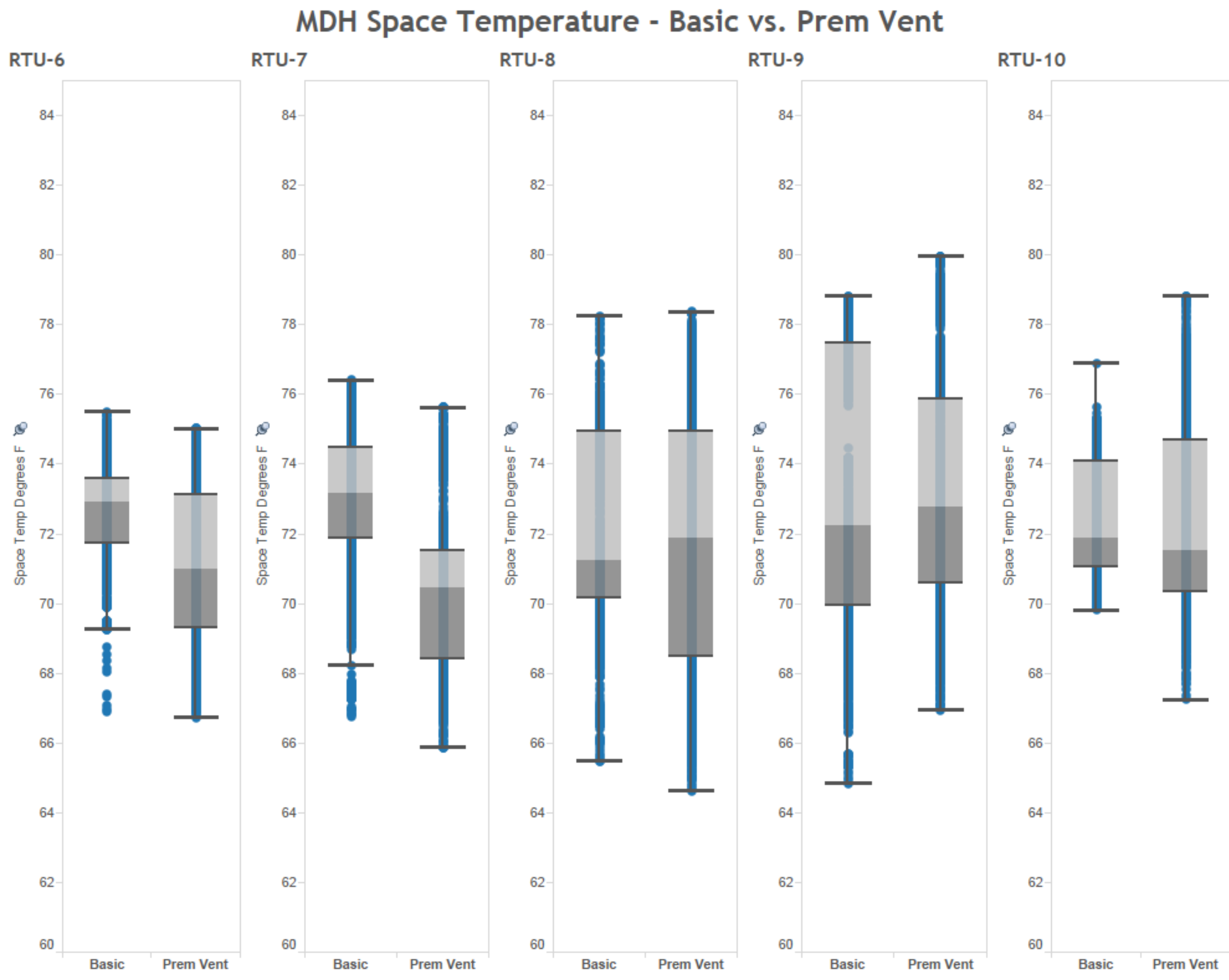


Figure 43. Space temperature box and whisker plots for MDH site (RTUs 11-15)

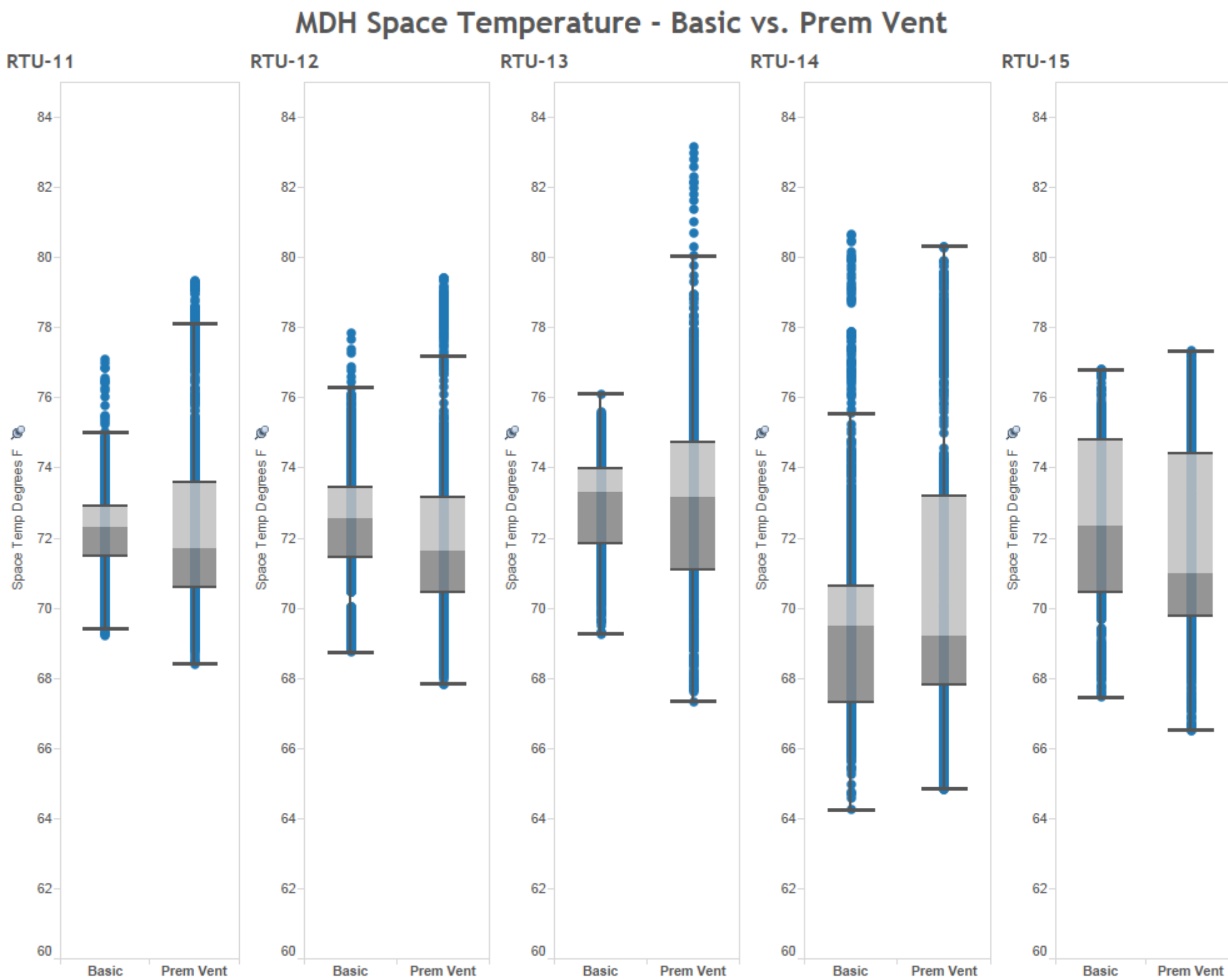


Figure 44. Space temperature box and whisker plots for MDH site (RTUs 16-20)

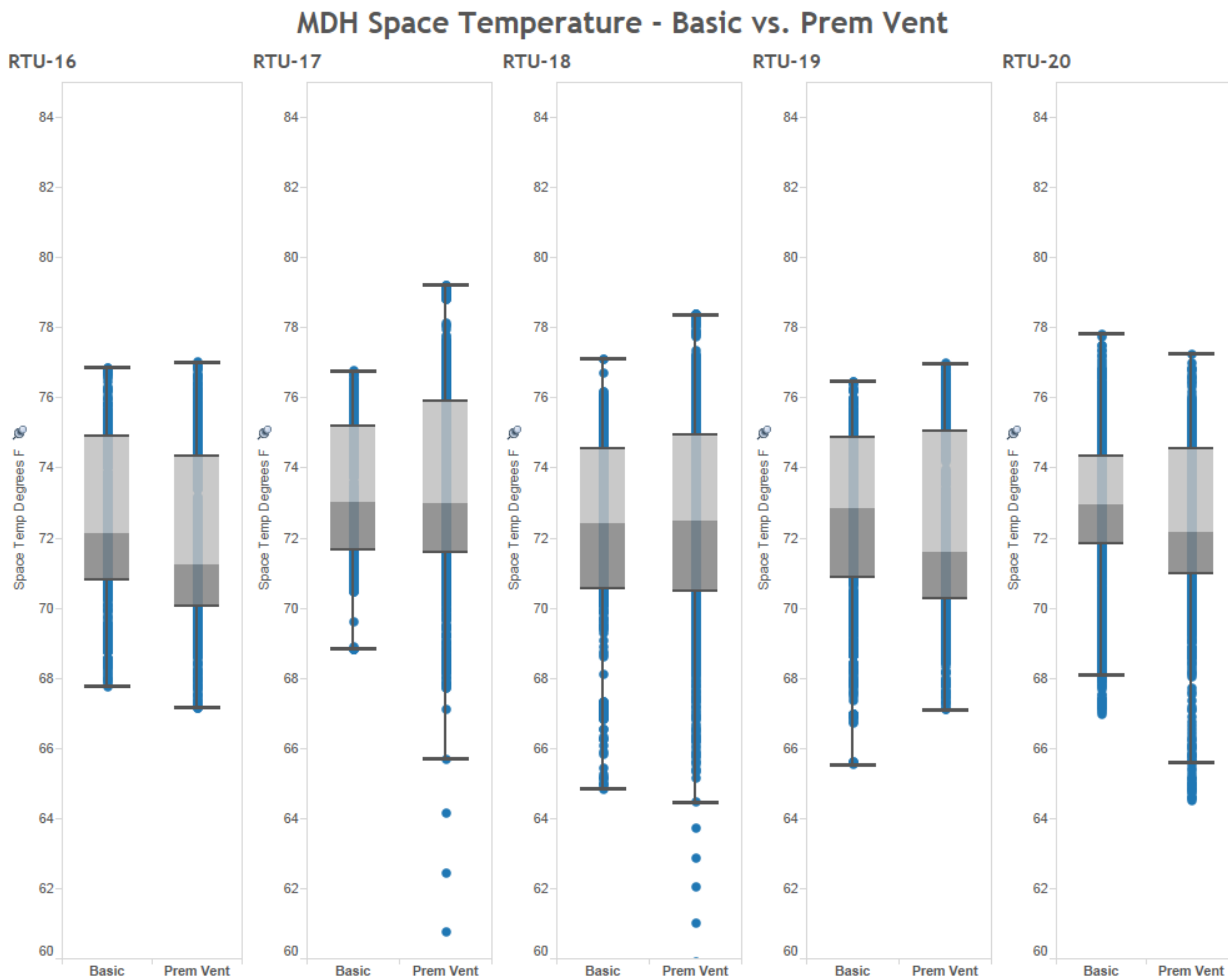


Figure 45. Space temperature box and whisker plots for MIN site (RTUs 1-3)

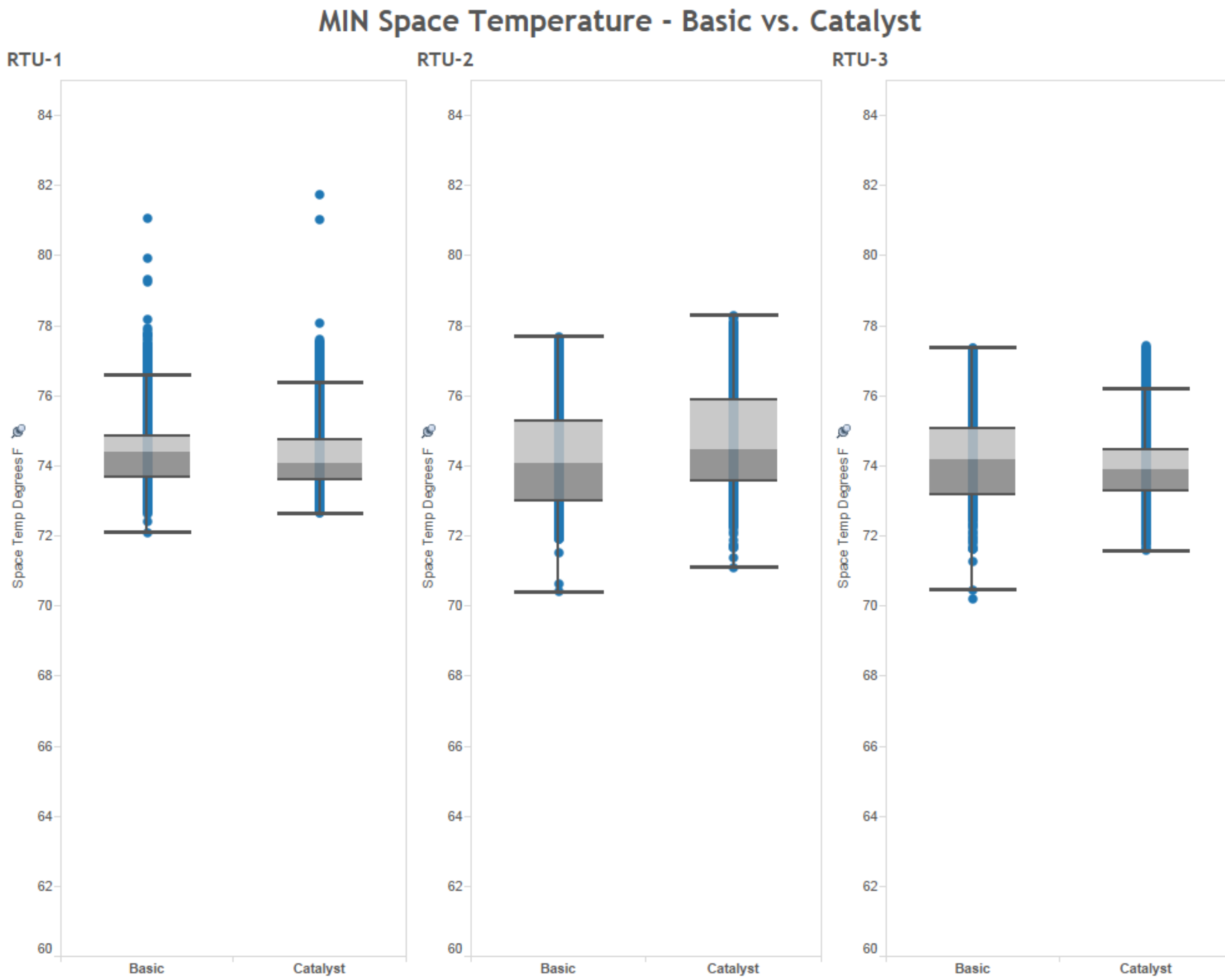


Figure 46. Space temperature box and whisker plots for MIN site (RTUs 4-6)

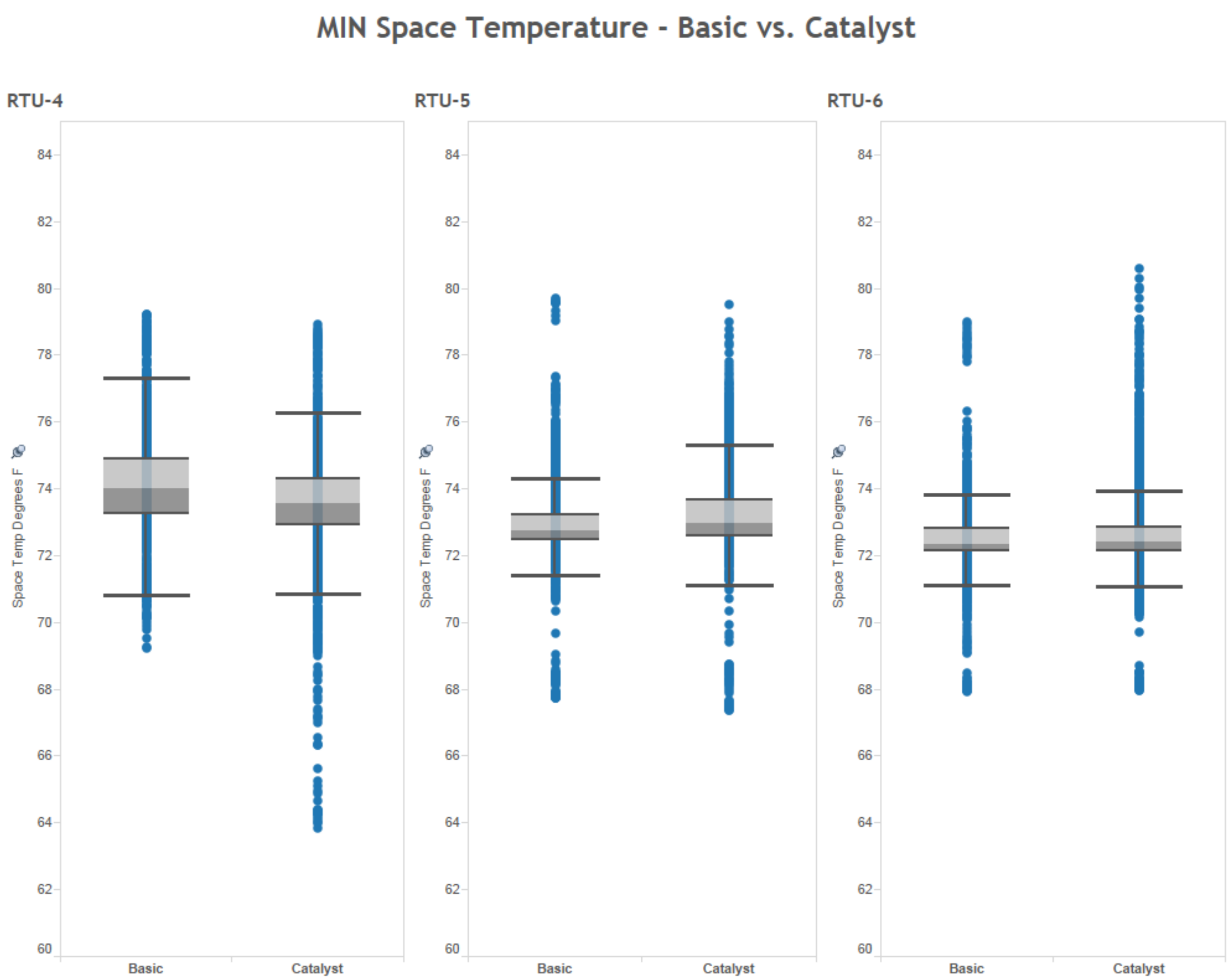


Figure 47. Space temperature box and whisker plots for NOW site

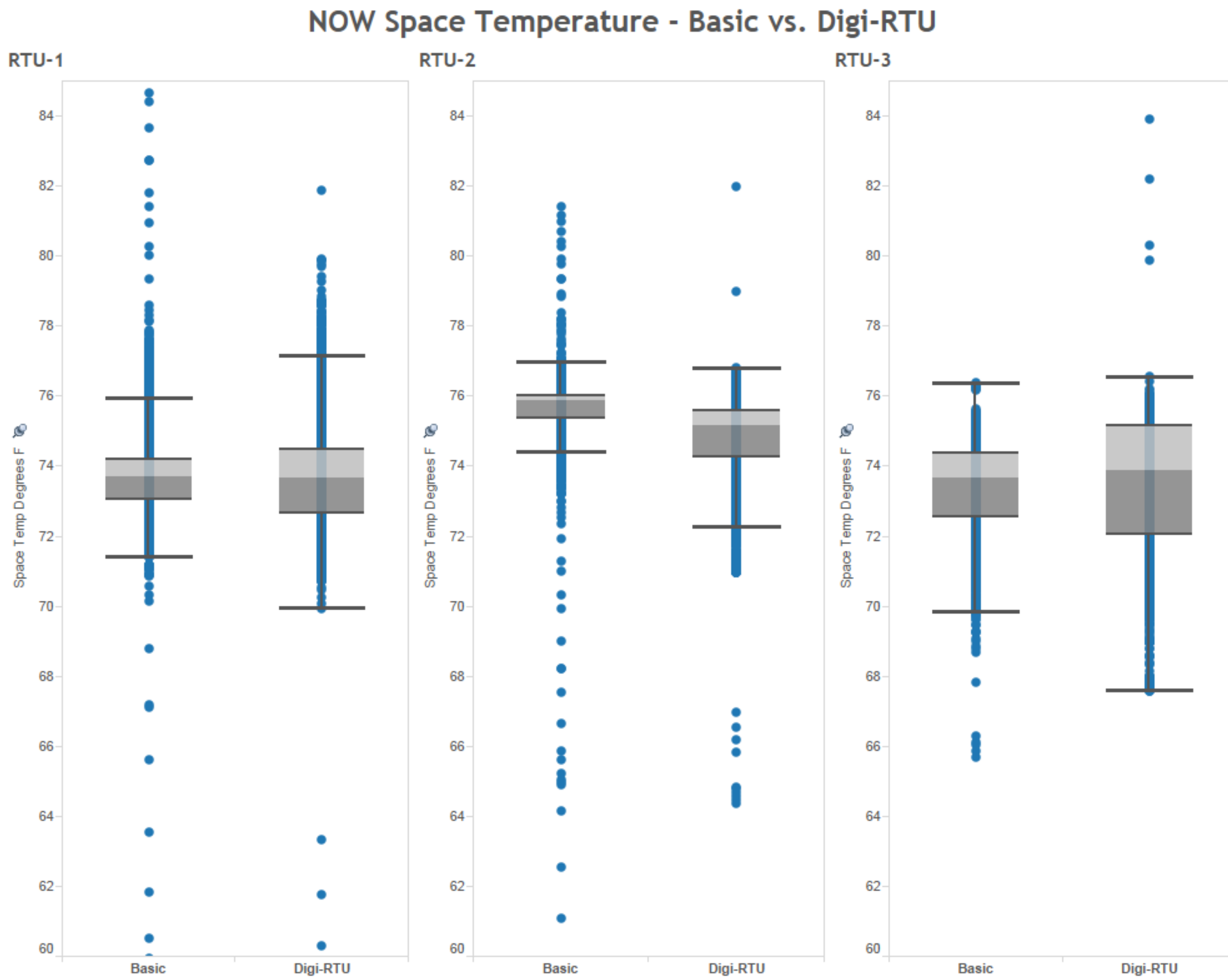


Figure 48. Space temperature box and whisker plots for NUR site (RTUs 1-5)

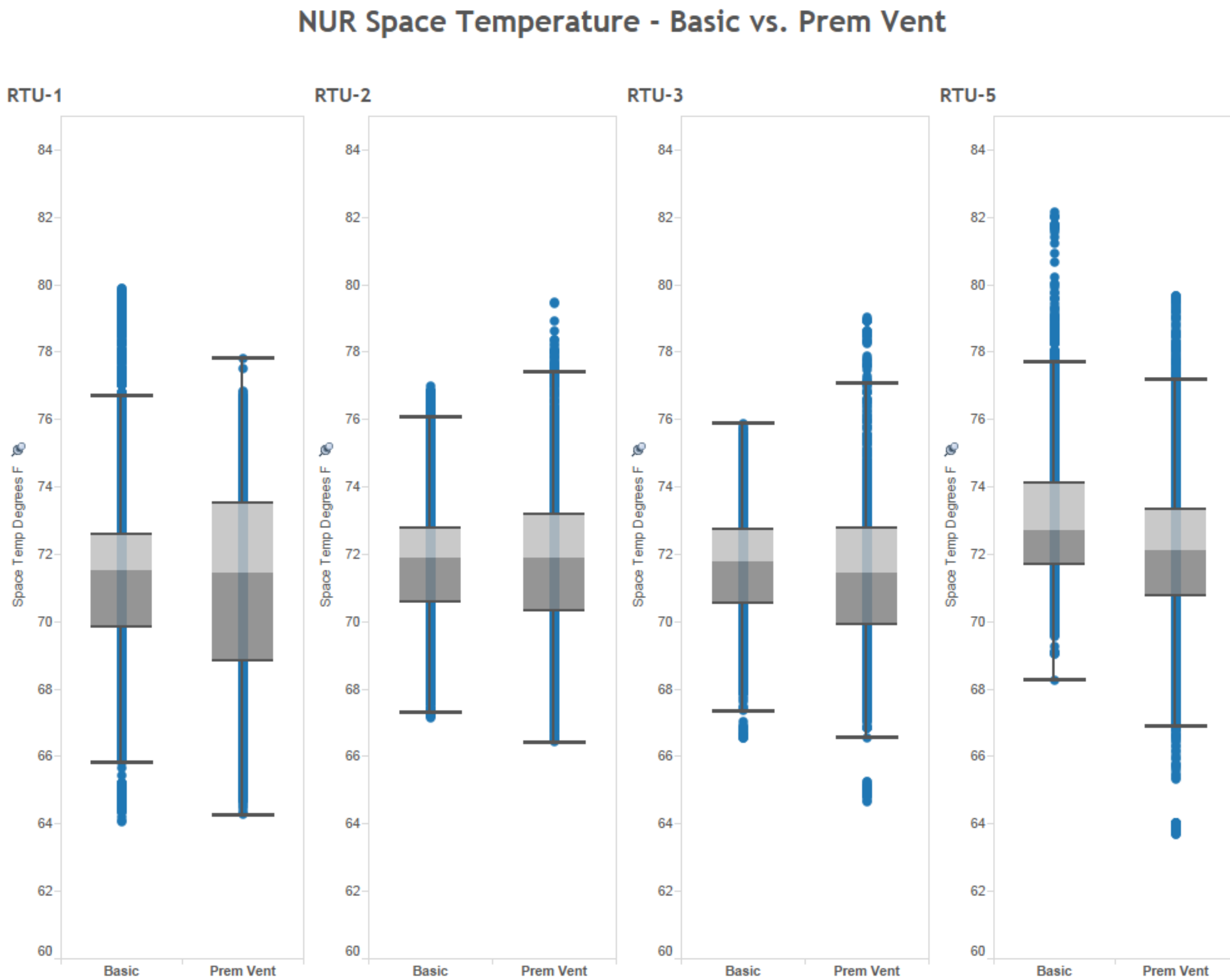


Figure 49. Space temperature box and whisker plots for NUR site (RTUs 6-8)

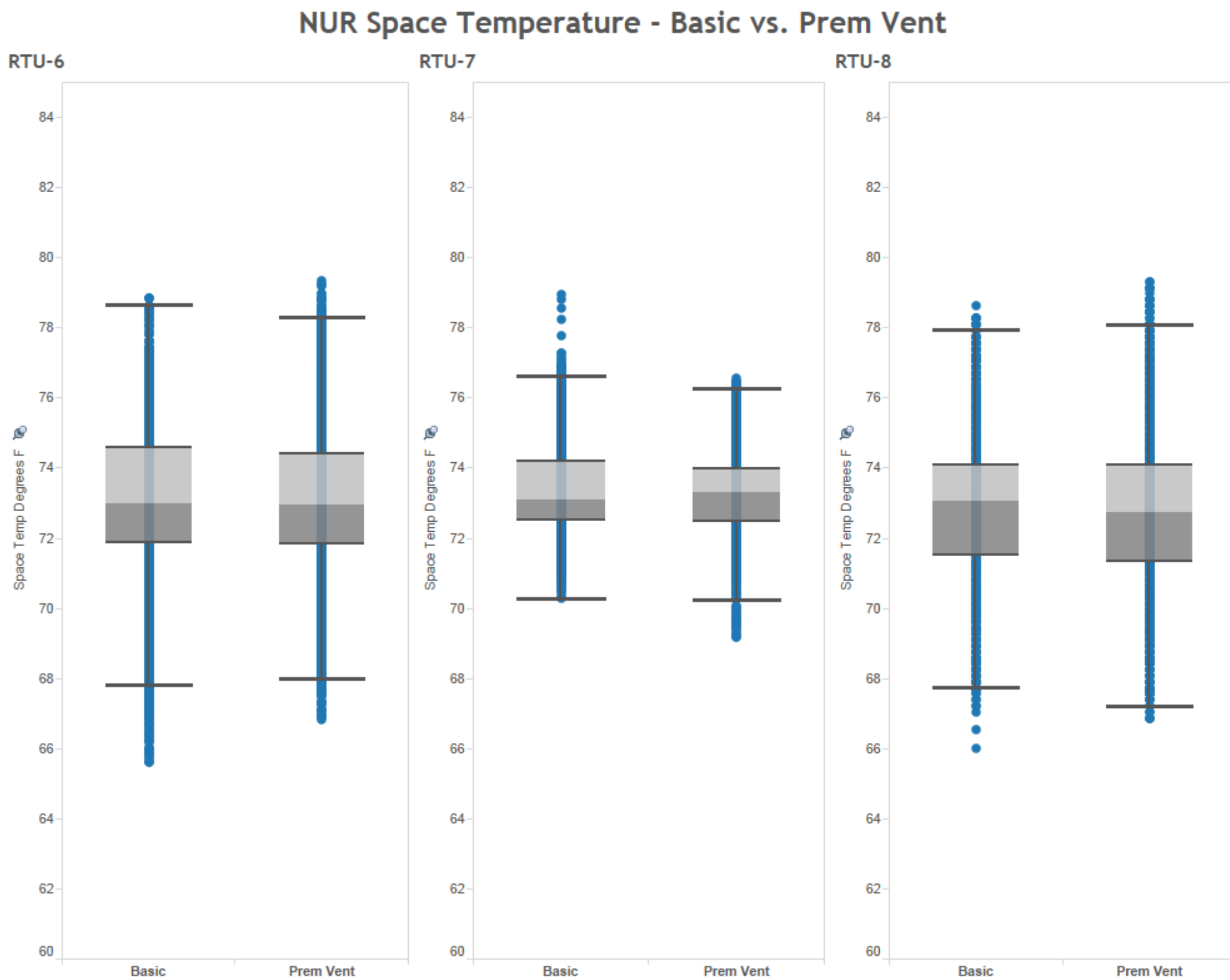


Figure 50. Space temperature box and whisker plots for SEI site (RTUs 1-4)

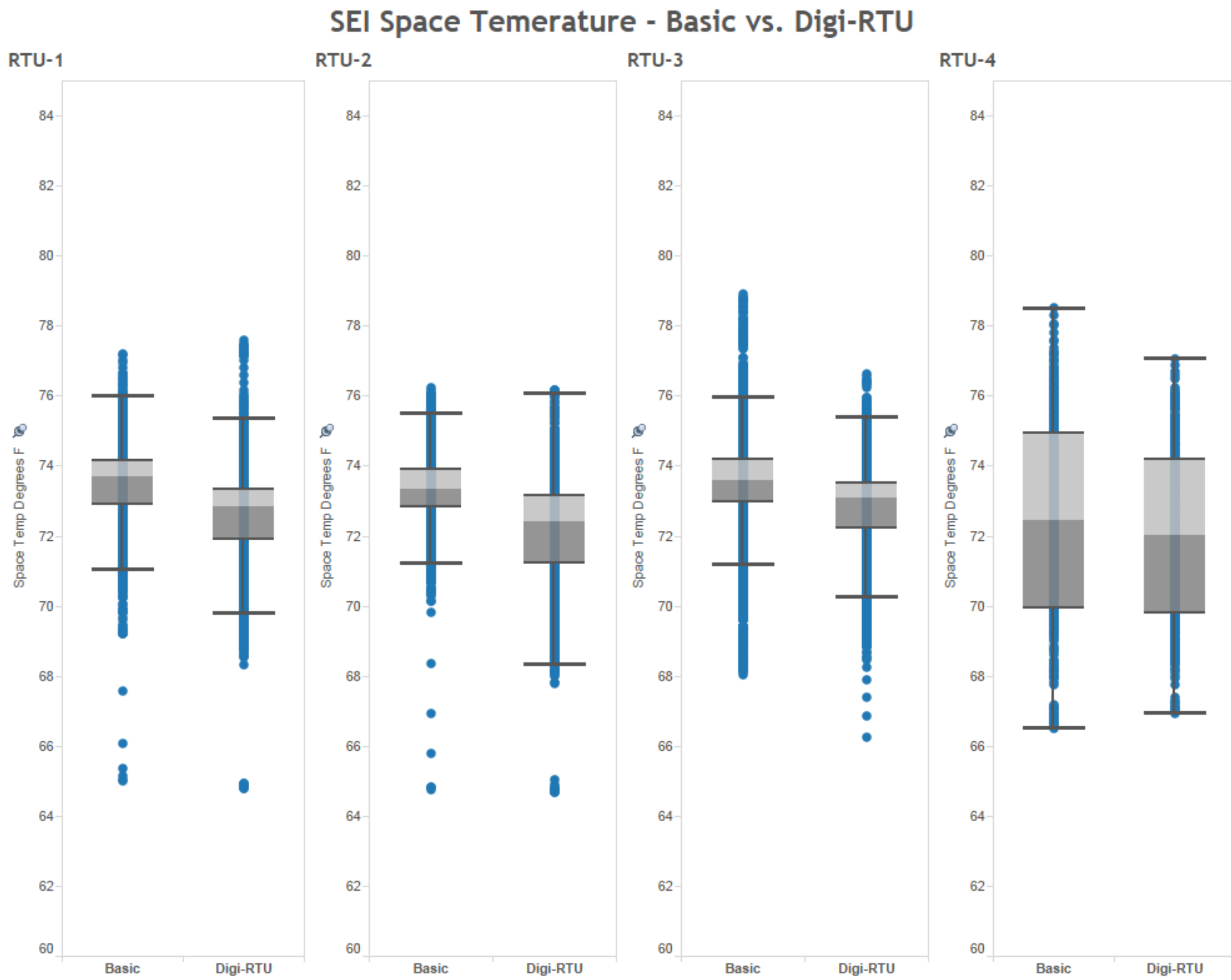
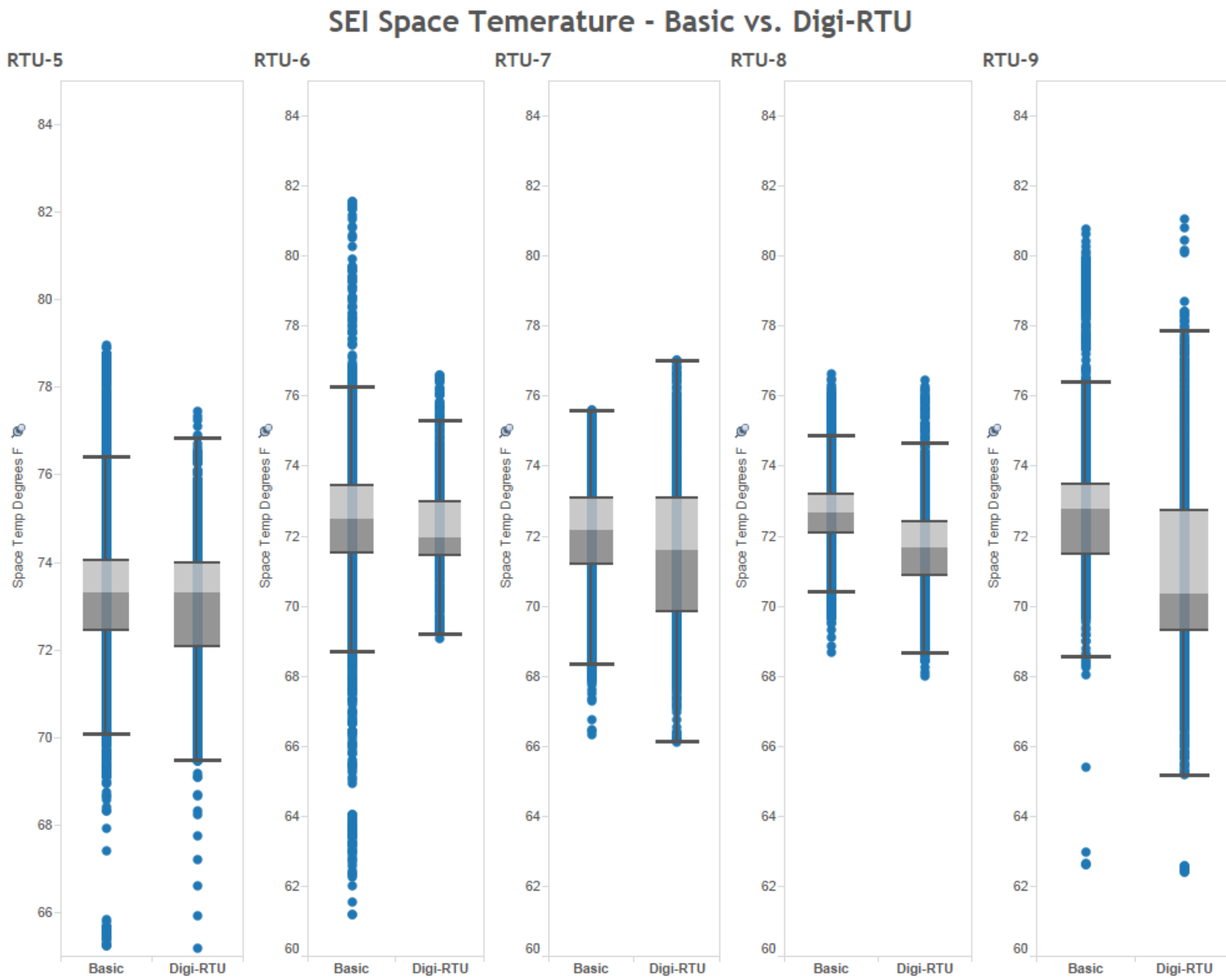


Figure 51. Space temperature box and whisker plots for SEI site (RTUs 5-9)



APPENDIX F – SPACE CO2

Figure 52. Overall Average Space CO2 Analysis for CEE Units

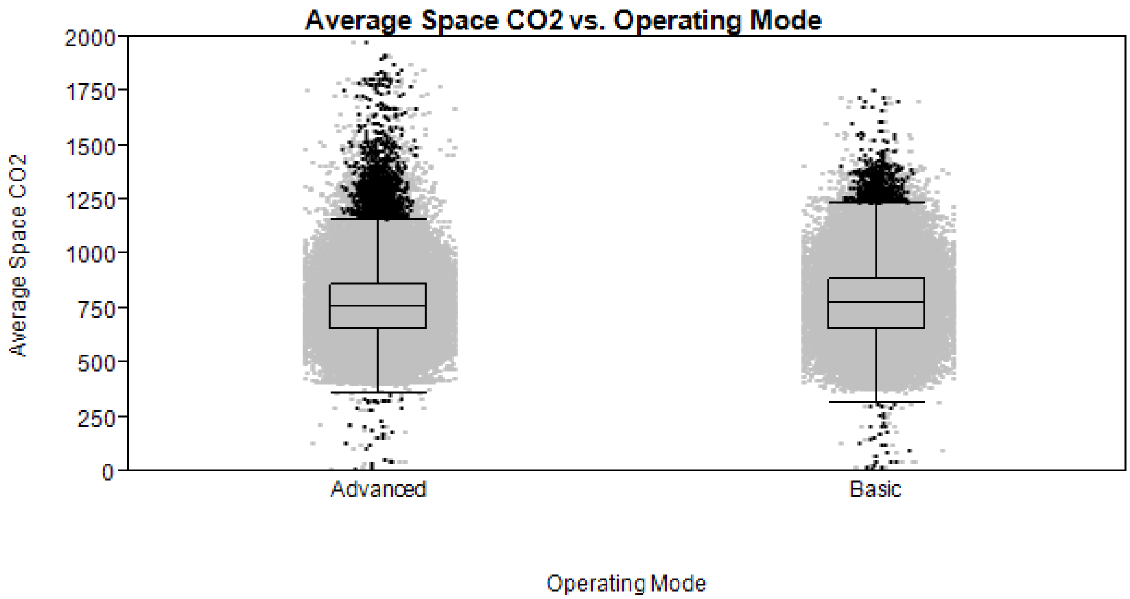


Figure 53. Average Space CO2 Analysis by Individual CEE Units

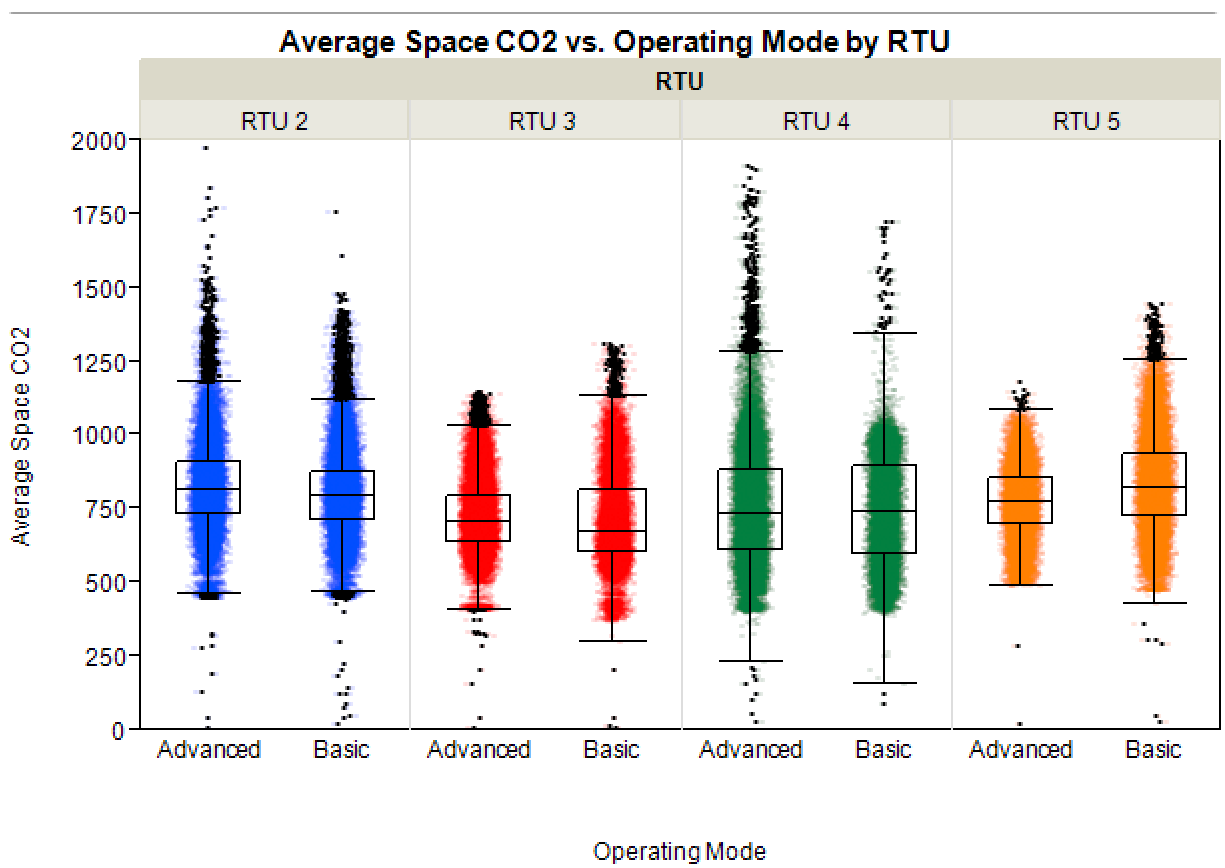


Figure 54. Overall Average Space CO2 Analysis for MIN Units

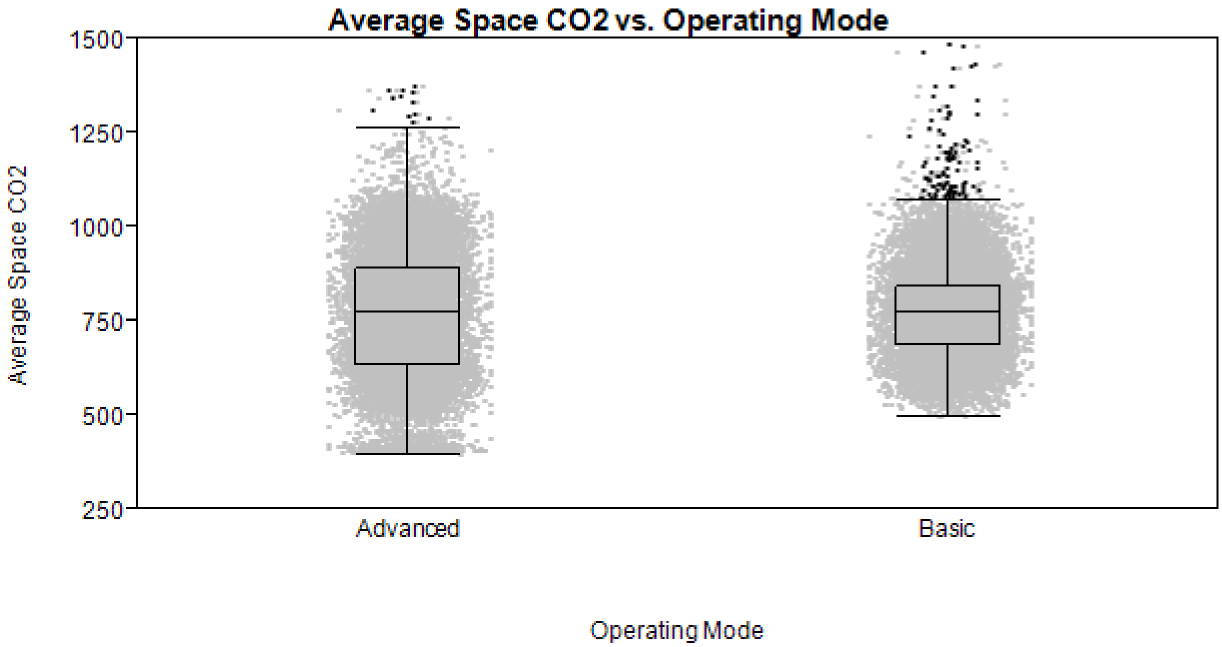


Figure 55. Average Space CO2 Analysis by Individual MIN Unit

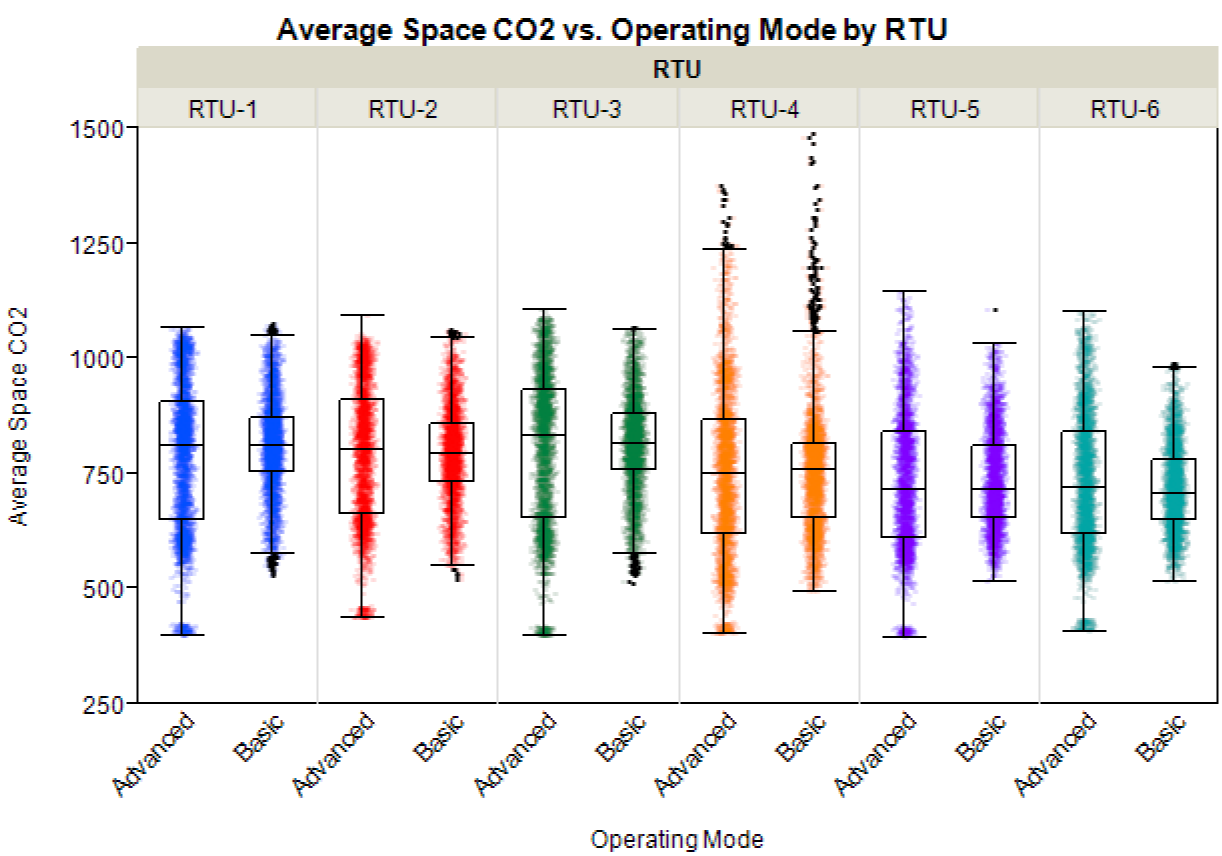


Figure 56. Overall Average Space CO2 Analysis for NOW Units

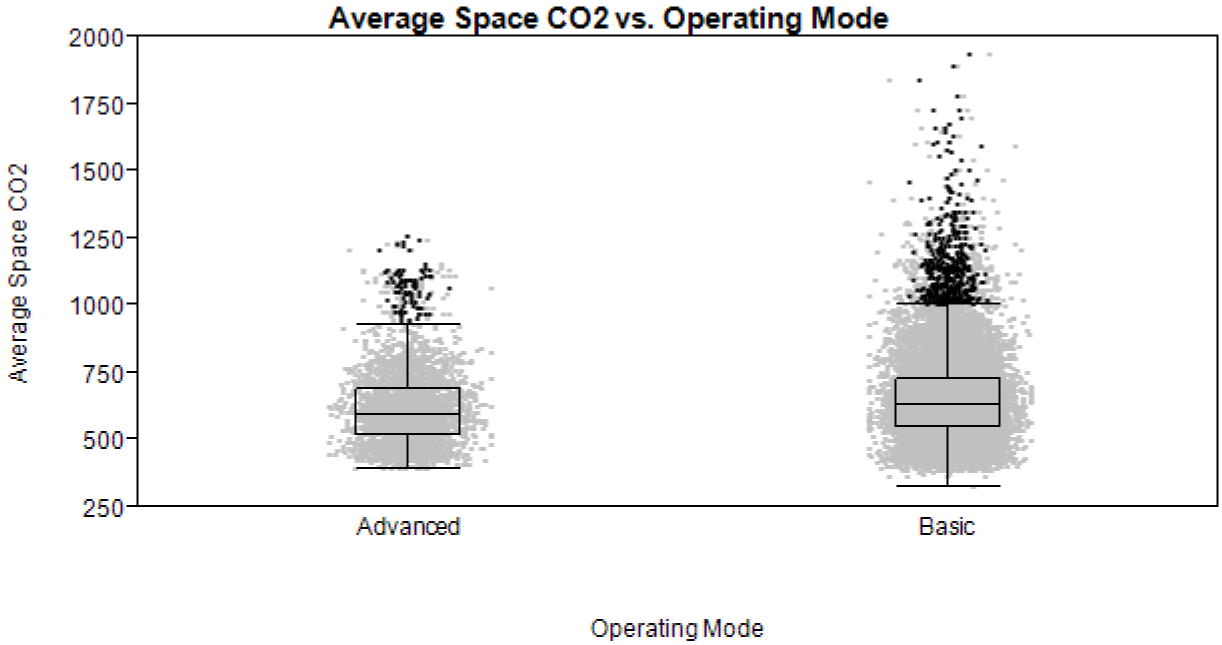


Figure 57. Individual Unit Average Space CO2 Analysis for NOW Units

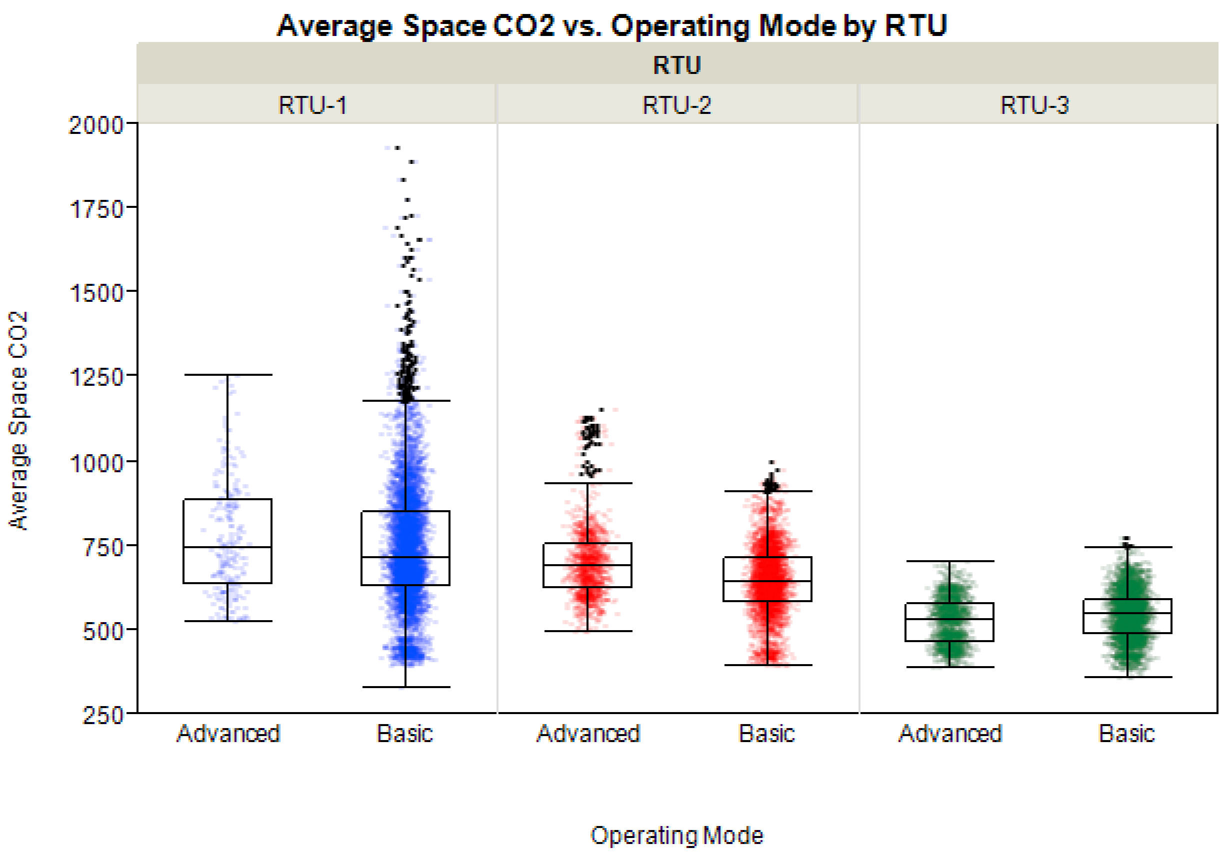


Figure 58. Overall Average Space CO2 Analysis for NUR Units

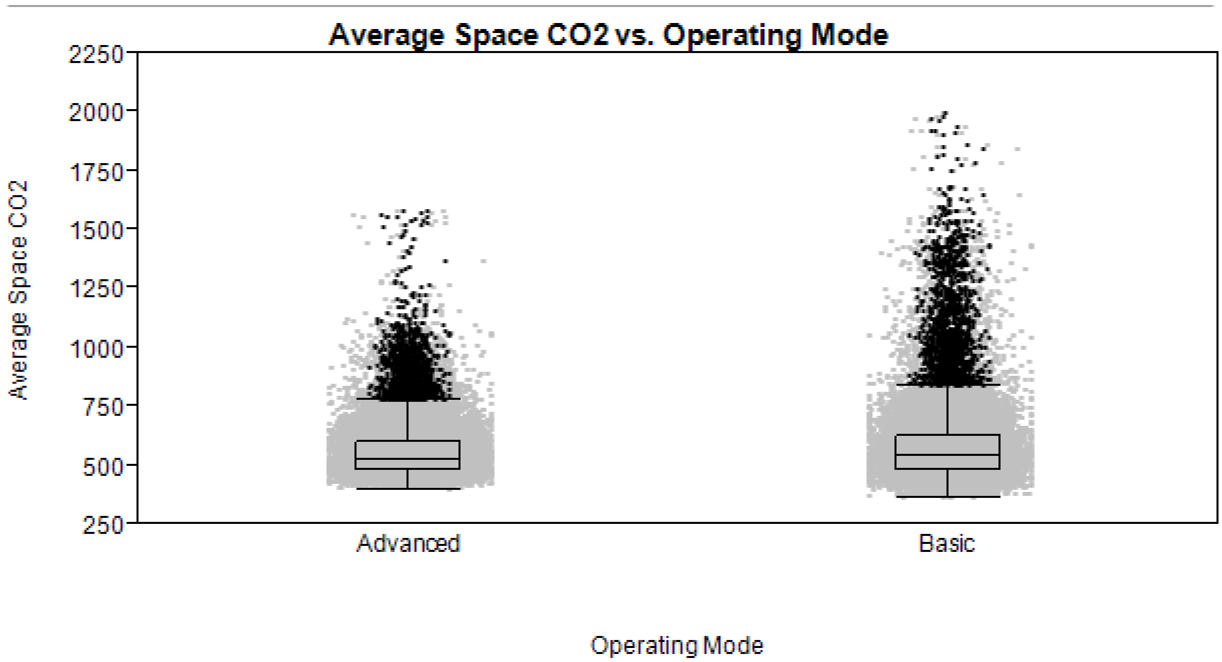


Figure 59. Individual Unit Average Space CO2 Analysis for NUR Units

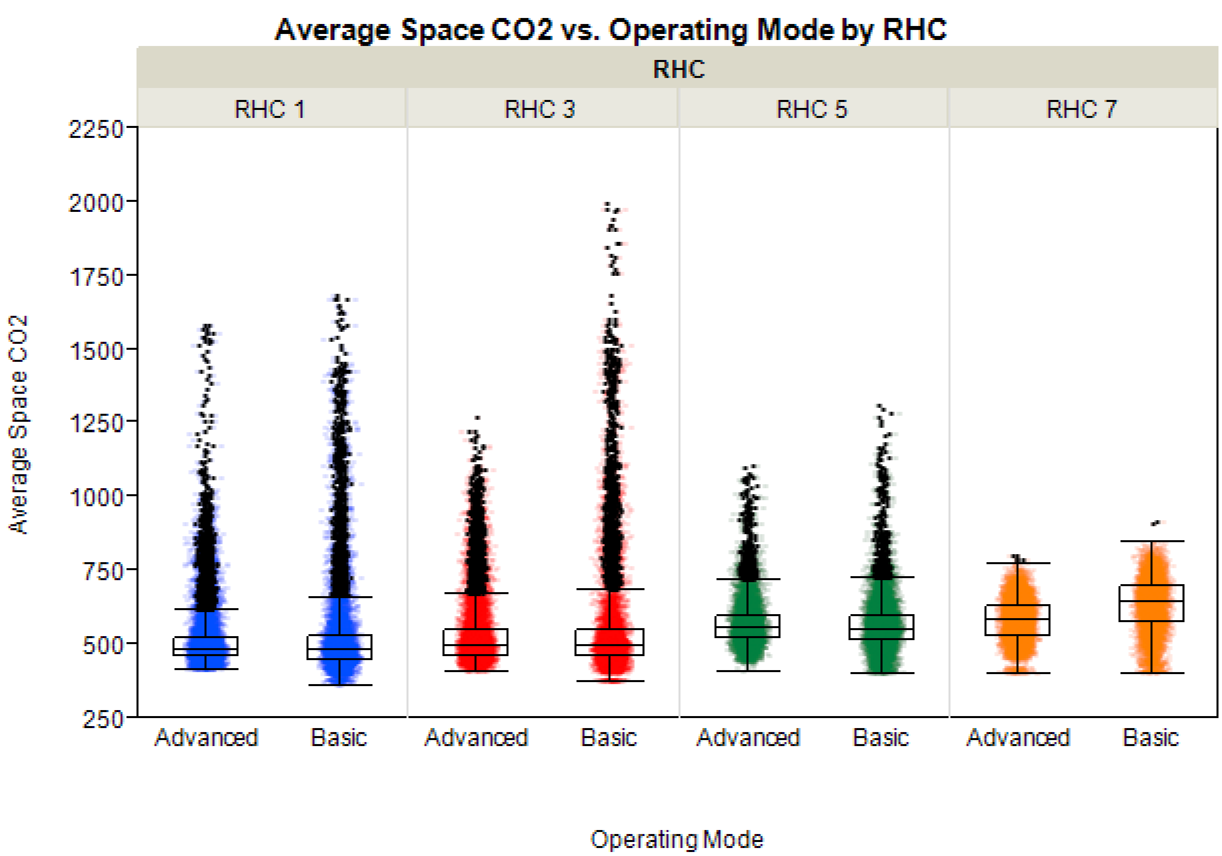


Figure 60. Overall Average Space CO2 Analysis for SEI Units

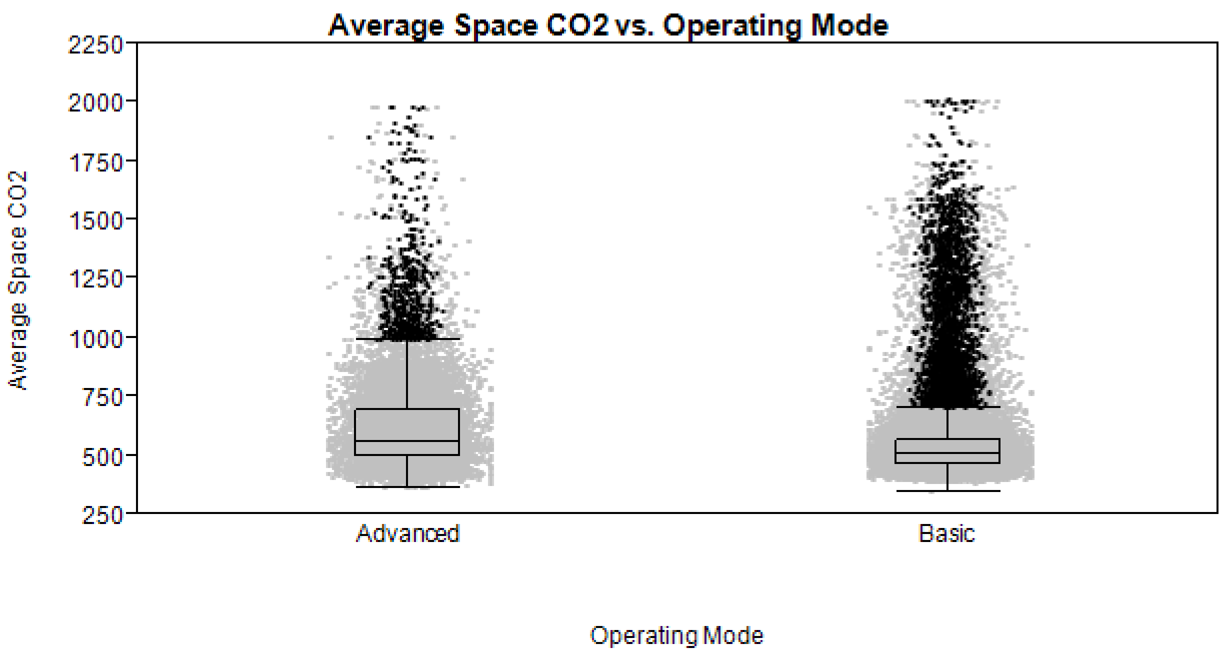


Figure 61. Individual Unit Average Space CO2 Analysis for SEI Units