Validation, Economics and Energy Savings for Advanced Commercial Rooftop Unit Control Strategies

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Packaged rooftop units (RTUs) serve over 60% (39 billion square feet) of commercial building floor space in the United States according to the U.S Energy Information Agency. As part of a rooftop unit challenge to reduce energy consumption across the commercial buildings sector, the United States Department of Energy (USDOE) funded a comprehensive evaluation of a retrofitted advanced RTU controller on 122 RTUs across multiple building types and climate zones in the U.S. To aid in this evaluation, the Pacific Northwest National Laboratory (PNNL) utilized software to analyze and validate the controller and the savings realized from the control strategies employed. The focus of this work was on the evaluation process of the controller, which included detecting faults using an air-side economizer diagnostic software tool called the Outdoor Air Economizer (OAE). The three primary faults that the tool identified were: supplying too much outdoor air; not supplying enough outdoor air; and economizing when there is no call for cooling. Across the portfolio of RTUs in the field, however, the data and results indicated that these units were economizing properly and not experiencing such faults when the controller was on.

I. INTRODUCTION

Packaged air-conditioners and heat pumps serve over 60% of the commercial building floor space in the United States, contributing to about 230 trillion Btus of energy consumption annually. Therefore, even a small increase in the operational efficiency of these units can lead to significant reductions in energy use and operating cost. As part of PNNL's Systems Engineering and Integration capability, an evaluation was performed of the improved Catalyst controller developed by Transformative Wave Technology (TWT). Figure 1 shows a schematic of a retrofitted rooftop unit with the controller and shows the areas that the controller impacts. The primary function of a rooftop unit is to provide air to the building space(s) it serves, and to satisfy the space temperature requirements for the space(s) by means or heating or cooling the air. The installed controller has a number of advanced functions on the RTUs. It can modulate the supply fan speed, control heating and cooling commands, and control the outdoor damper position. The controller can also record measurements on things such as damper commands (percent open), total RTU electric power (kWh), fan speed (Hz) and temperatures (°F).

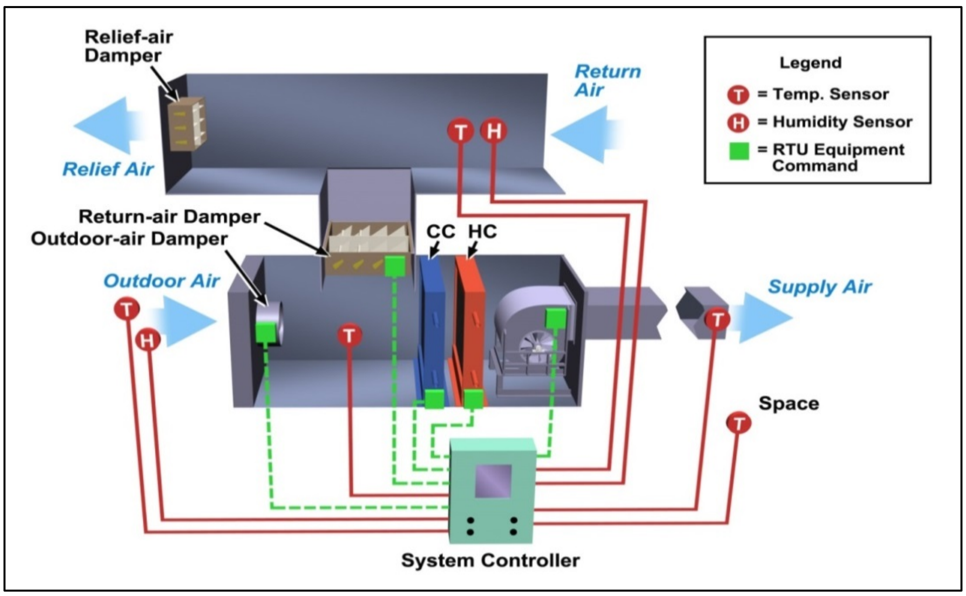

Figure 1: Example of a packaged rooftop unit; equipped with an economizer, cooling and heating coil and supply fan arrangement ***(Wang, et al, Publication Pending.)***

One of the primary objectives of this evaluation was to validate that the controller operated as according to the control strategy during the Energy Savings Mode. This consisted of three primary energy efficiency: supply-fan speed control, demand control ventilation (DCV), and integrated air-side economizer control. This report presents the approach and findings when validating the air-side economizer operation on 63 RTUs at eight sites. These eight sites cover four building types, including mercantile (both retail and shopping malls), office, food sales, and healthcare. Of the 63 RTUs, 18 are heat pumps and 45 are air conditioners with gas heat. The buildings are located in four different climate zones including 3B (warm-dry), 4A (mixed-moist), 4C (mixed-marine), and 5A (cool-moist) (ASHRAE 2010a)

II. METHODS

The two approaches used to analyze the economizer consisted of identifying if the unit was economizing (utilizing free cooling) when outside air conditions were ideal for economizing and comparing the commanded amount of outdoor air (which is determined by the damper command) to the actual amount of outdoor air (which is calculated by a ratio of temperatures and is shown below).

The measured outdoor air temperature (OAT), mixed air temperature (MAT), discharge air temperature (DAT) and return air temperatures (RAT) were used to assess the operation efficiency of the Catalyst Controller on these RTUs. The outdoor air fraction (OAF) gives the total fraction of outdoor air supplied to an RTU as

$$\mathrm{OAF} = \frac{(\text{Mixed Air Temperature} - \text{Return Air Temperature})}{(\text{Outdoor Air Temperature} - \text{Return Air Temperature})}.$$

A high OAF should occur when the damper is commanded fully open and a low OAF should occur when the damper is commanded to its minimum position. Therefore, the use of tables showing the OAF at a specified damper command can help identify the effectiveness of the economizer operations. The unit should economize only when there is a need for cooling and the outdoor conditions are favorable for economizing.

An airside diagnostic software tool (AirDx) was used to validate that the controller was operating efficiently under these control strategies. Further investigations into the temperature relationships were conducted to confirm the findings from the AirDx. Lastly, tables were used to validate the calculated OAF when the damper was commanded to its minimum and maximum position for all sites examined in the study. If the damper is commanded to the minimum (5-15 % open), there should be an OAF of less than 20% (not exact due to errors in temperature measurements). On the contrary, if the damper is commanded to the maximum (100% open), then there should be a high OAF of nearly 100%.

III. FINDINGS AND DISCUSSION

All data for the 63 units were run through the AirDx software tool. The output is displayed by month with each column representing one day ascending from left to right within one month and each square representing one hour ascending from top to bottom within one day. Figure 2 shows the output from the tool for RTU 380. The red, blue, and yellow colors represent errors in the functionality of the unit. Errors include but are not limited to: Inadequate outdoor air ventilation, too much outdoor air ventilation, not economizing when conditions are favorable, temperature sensor errors, etc.

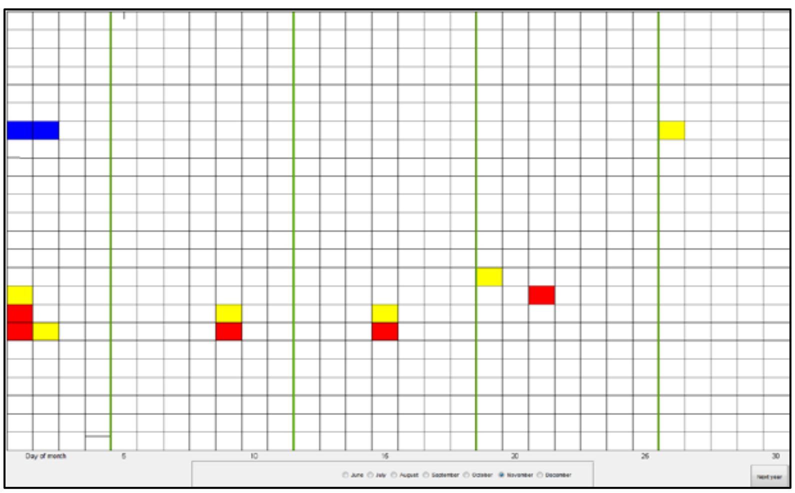

Figure 2: Output from air side diagnostic software tool for RTU 380 in November, 2012.

One primary finding in this project can be highlighted in Figure 2; there are very little errors during the Energy Savings Mode. This means that overall the unit is operating efficiently and is saving energy. Because this represents only one month for the unit, simple charts can be generated to further investigate the temperature relationships to confirm these findings. Figure 3 shows mixed air temperature versus outdoor air temperature when the damper is commanded fully open. Note the one to one relationship between MAT and OAT, which means that the mixed air temperature in the mixed-air chamber is comprised of mostly outdoor air and is taking full advantage of the outdoor air conditions. Most of the RTUs at this site (43) economized properly.

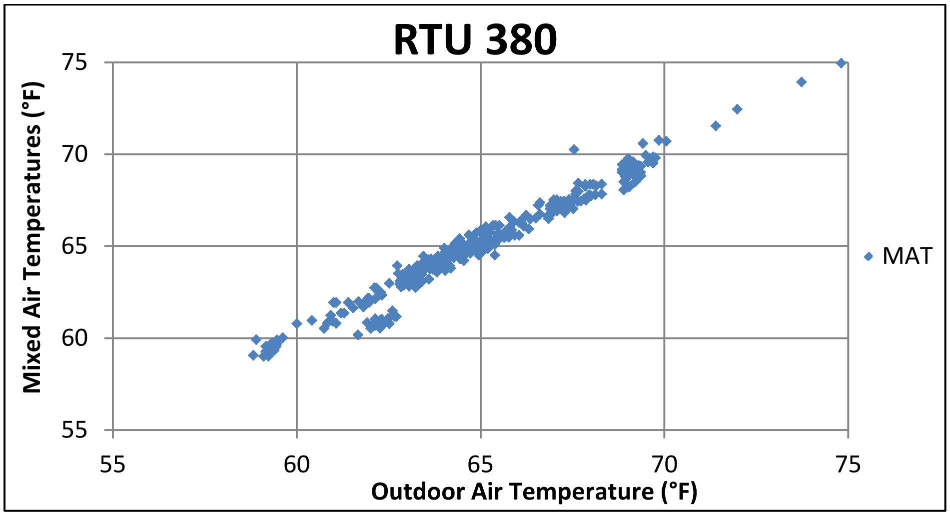

Figure 3: Mixed air temperature versus outdoor air temperature when the damper is commanded 100% open for RTU 380.

A second finding is inefficient operation of the controller on the RTUs. Figure 4 shows the output from the AirDx tool for RTU 387. The only consistently efficient operation appears to be in the early morning, shown in white, where there are no errors.

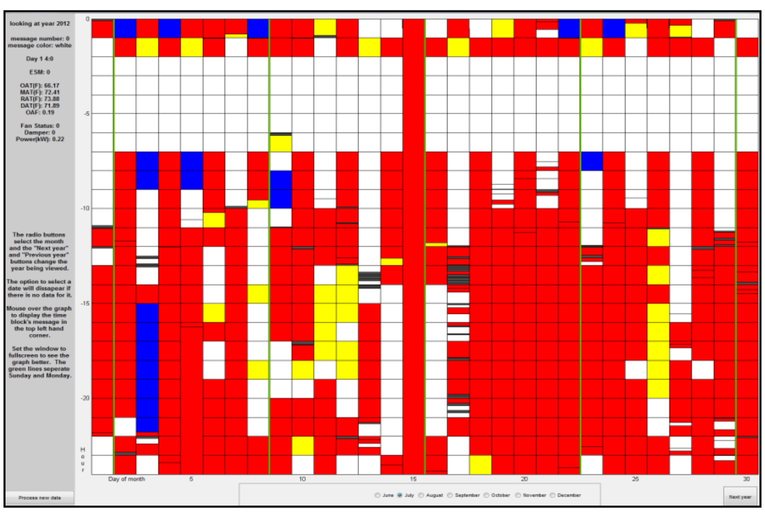

Figure 4: Output from air side diagnostic software tool for RTU 387 in July, 2012.

The abundance of red in the above figure indicates the problem of not fully taking advantage of economizing conditions. Several other units at site 44 exhibited similar problems. This problem may be caused by real damper problems (stuck damper, broken actuator, etc.) or temperature sensor faults. Figure 5 shows the MAT versus the OAT when the damper is commanded fully open and is economizing for RTU 387 at site 44. Figure 5 confirms the findings of inefficient operation in RTU 387 by the non-linear relationship seen between the MAT and OAT.

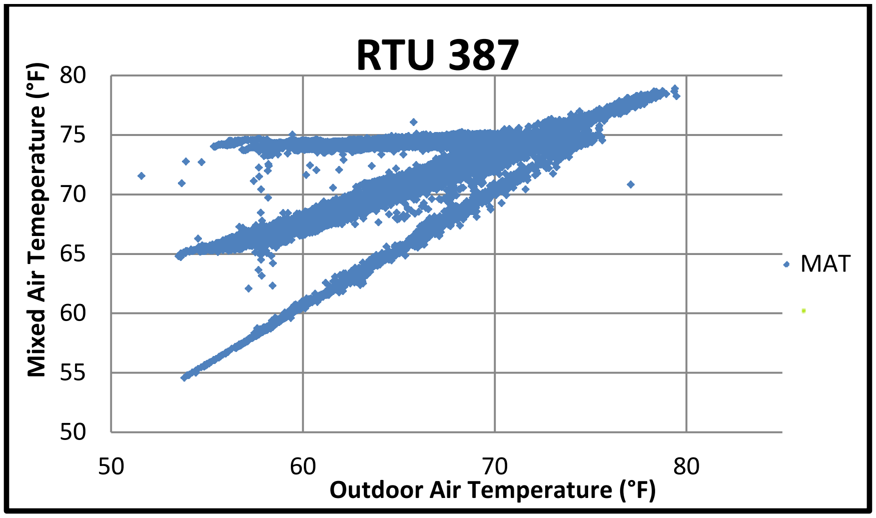

Figure 5: Mixed air temperature versus outdoor air temperature when the damper is commanded 100% open for RTU 380.

Figure 5 demonstrates that little outdoor air is being brought into the mixed-air chamber when economizing and not taking advantage of the free cooling opportunities. The figure does not contain a one to one relationship seen in figure 3 and instead shows 5 to 15 °F higher than the OAT when the damper is commanded fully open. Because these findings are only for single units, tables can be generated to show the average OAF across all sites. Appendix A contains all tables generated for the RTUs at each site. Table 1 shows the average OAF (expressed as a percentage) data for each site as it fits into calculated OAF ranges when the damper is commanded to a minimum position. Ideally, the OAF should be less than 10% because the damper is commanded to its minimum position. Sites highlighted in yellow have good operation but site 40 on the right, highlighted in pink, is bringing in too much outdoor air and potentially wasting energy.

Table 1: Distribution of the calculated OAF by site when the damper is commanded to the minimum position *(Wang, et. al, Publication Pending)*.

Site ID	Number of RTUs	OAF Range		
		≤10%	10%-20%	≥20%
28	27	37%	37%	26%
39	2	96%	2%	2%
40	8	17%	32%	51%
41	1	68%	12%	21%
43	6	84%	13%	3%
44	11	95%	2%	3%
46	2	84%	12%	4%
51	5	100%	0%	0%

This fault, over-ventilation, occurs when there is too much outdoor air being supplied when the expected OAF exceeds the minimum expected OAF at times when the damper is commanded to the minimum position.

Table 2, on the other hand shows the average OAF (expressed as a percentage) for each site as it fits into calculated OAF ranges when the damper is commanded to its maximum position. This table shows the percentage of data records with the calculated OAF in the ranges of 70-100%, 50-70% and less than 50% by site when the controller commands the damper to be 100% open. Sites highlighted in yellow have good operation but site 39 highlighted in yellow is not taking advantage of the available free cooling. When the damper is commanded fully open, the maximum amount of outdoor air is provided to the RTU for cooling or supplementing mechanical cooling. All of the air provided to the RTU will be outdoor air, ideally, when the damper is fully open. When less than 100% of the air provided to the RTU is outdoor air the remainder will be comprised of warmer and less favorable return air from the space.

Table 2: Distribution of calculated OAF by site when the damper is commanded to the maximum position *(Wang, et. al, Publication Pending)*.

Site ID	Number of RTUs	OAF Range		
		≤50%	50%-70%	≥70%
28	27	10%	29%	61%
39	2	93%	7%	0%
40	8	0%	0%	100%
41	1	22%	41%	37%
43	6	6%	7%	88%
44	11	38%	23%	39%
46	2	5%	3%	92%
51	5	18%	25%	57%

Overall, results from Tables 1 and 2 indicated that the units were economizing properly when utilizing the advanced control strategies. The sites that were less efficient may have damper issues or temperature sensor errors. If RTUs perform similar to the ones in Site 39, it means the RTU is not taking advantage available free cooling and is thus using mechanical cooling to cool and discharge the air to the building space.

IV. CONCLUSION

A total of 63 RTUs were retrofitted with a commercially available advanced controller for improving RTU operational efficiency. By enhancing the economizer through the implementation of this advanced controller, the energy and cost savings have a huge potential. The economizer allows the RTU to use cool outdoor air to satisfy the cooling needs of the space instead of mechanical cooling; thus lowering the amount of energy the RTU uses to meet the cooling needs of the building. The procedure for validating the economizer was successful by using measured temperature data, damper commands and cooling signals.

Generating tables which show the percentage of outdoor air can conclude that problems of over-ventilation, for the most part, do not exist. These tables also show that, overall, most sites in the study were economizing when commanded to do so. In the few cases when the calculated OAF is less than 50%, yet the desired OAF is greater than 70%, there may be damper or temperature sensor errors. This research was successful in testing and validating advanced control strategies for packaged rooftop units used on commercial buildings. This report, however, does not justify the cost savings for the controller, and the reader should read the PNNL report once released for more information on justifying use of the advanced controller..

V. ACKNOWLEDGEMENTS

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APPENDIX A

Outdoor Air Fraction for All Sites

Table A- 1. Outdoor Air Fraction for Alderwood Mall Site 28

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
28	202	19%	23%	28%	none	52%	71%
28	203	29%	36%	26%	60%	43%	none
28	204	67%	20%	35%	61%	51%	79%
28	205	21%	9%	6%	27%	1%	none
28	206	48%	45%	37%	none	40%	none
28	207	33%	27%	2%	80%	2%	45%
28	209	66%	67%	73%	94%	81%	90%
28	210	15%	2%	2%	68%	2%	67%
28	212	10%	21%	3%	67%	3%	63%
28	213	15%	6%	3%	65%	2%	none
28	214	66%	79%	100%	79%	99%	none
28	215	51%	51%	49%	none	57%	none
28	216	none	48%	56%	none	76%	none
28	217	30%	37%	38%	59%	44%	none
28	218	98%	67%	60%	96%	63%	71%
28	219	64%	75%	13%	96%	7%	93%
28	220	26%	26%	49%	98%	33%	96%
28	221	39%	28%	21%	63%	33%	61%
28	222	25%	1%	3%	17%	3%	none
28	223	50%	21%	3%	66%	2%	none
28	224	60%	78%	86%	103%	100%	none
28	225	101%	48%	38%	none	43%	none
28	226	73%	42%	37%	56%	45%	none
28	227	49%	25%	none	29%	none	none
28	228	47%	49%	41%	56%	49%	62%

Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
28	229	2%	2%	2%	none	3%	none
28	230	*RTU 230 is off for entire study*				none	none
28	231	78%	16%	58%	93%	89%	none
39	363	27%	3%	1%	8%	5%	19%

Table A- 2. Outdoor Air Fraction for Cleveland Clinic Site 39

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
39	362	7%	17%	7%	21%	11%	31%
39	363	27%	3%	1%	8%	5%	19%

Table A- 3. Outdoor Air Fraction for BJ's Wholesale Site 40

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
40	364	30%	31%	28%	115%	34%	109%
40	365	30%	33%	32%	112%	55%	None
40	366	34%	34%	28%	105%	62%	None
40	367	33%	35%	41%	None	45%	None
40	368	29%	26%	36%	106%	58%	None
40	369	29%	36%	45%	110%	57%	100%
40	370	35%	47%	63%	106%	66%	105%
40	371	21%	19%	13%	108%	53%	104%

Table A- 4. Outdoor Air Fraction for Banner Bank Site 41

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
41	372	21%	19%	15%	89%	31%	86%

Table A- 5. Outdoor Air Fraction for Everett Service Center Site 43

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
43	375	22%	40%	24%	97%	33%	82%
43	376	6%	5%	4%	71%	9%	70%
43	377	6%	5%	16%	79%	14%	76%
43	378	11%	14%	5%	77%	7%	76%
43	379	23%	17%	23%	58%	23%	76%
43	380	3%	5%	5%	101%	22%	81%

Table A- 6. Outdoor Air Fraction for Federal Way Site 44

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
44	381	1%	1%	4%	53%	2%	50%
44	382	1%	2%	4%	55%	4%	5%
44	383	71%	69%	8%	59%	12%	58%
44	384	1%	1%	3%	89%	1%	39%
44	385	3%	3%	4%	72%	5%	45%
44	386	13%	13%	21%	76%	12%	47%
44	387	2%	2%	3%	27%	4%	38%

Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
44	388	3%	4%	7%	58%	5%	
44	389	6%	7%	19%	78%	8%	56%
44	390	2%	2%	9%	69%	6%	62%
44	391	7%	9%	14%	68%	9%	68%

Table A- 7. Outdoor Air Fraction for Whole Foods Site 46

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
46	407	21%	19%	15%	89%	31%	86%
46	409	7%	8%	7%	27%	6%	None

Table A- 8. Outdoor Air Fraction for Staples-Bellevue Site 51

		ESMMode ON				ESMMode OFF	
Site ID	Unit #	OAF @ 5.55% Damper Command	OAF @ 6.67% Damper Command	OAF @ 12.5% Damper Command	OAF @ 100% Damper Command	OAF @ 20% Damper Command	OAF @ 100% Damper Command
51	423	19%	4%	6%	none	3%	none
51	424	19%	6%	10%	65%	7%	54%
51	425	27%	5%	7%	80%	3%	62%
51	426	13%	3%	3%	29%	4%	26%
51	427	29%	8%	9%	85%	13%	82%