Improving Operating Efficiency

Of Packaged Air Conditioners & Heat Pumps

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Packaged rooftop units (RTUs) condition many different building types, in many climate locations, accounting for 46% (2.1 million) of all commercial buildings, serving over 60% (39 billion ft^2) of the commercial building floor space in the U.S.[1] Primary energy use associated with these units is more than 1,000 trillion Btus (293 billion kWh).[2] This article discusses several control strategies that can significantly reduce energy consumption associated with RTUs. Although all of these strategies are widely used in built-up air-handling units, they are not commonly used in existing RTUs. Both simulation and field evaluations show that adding these control strategies to existing RTUs can reduce their energy consumption by between 30% and 60%.

Background

Improving the rated efficiency of RTUs will yield energy savings; however, because systems tend to operate at off-design or part-load conditions for a significant period of time, improving the part-load performance of RTUs has far greater impact on energy savings. More importantly, measures that address the operational efficiency apply to both existing and new units.

Building codes require that when a building is occupied, the supply fan should operate continuously to meet the ventilation needs, regardless of whether the RTU provides cooling or heating. A significant portion of the RTUs in the field have constant-speed supply fans. Because the supply fan runs continuously during occupied periods, the fan energy consumption can be greater than the compressor energy consumption in many locations in the U.S. This implies that a big potential exists to achieve energy savings from the supply-fan speed control strategies.

Studies have shown that demand-controlled ventilation (DCV) can save significant energy in climates that are not favorable for economizing or that have a significant cooling/heating load.[3,4] Traditional DCV strategies modulate the outdoor-air damper to reduce the

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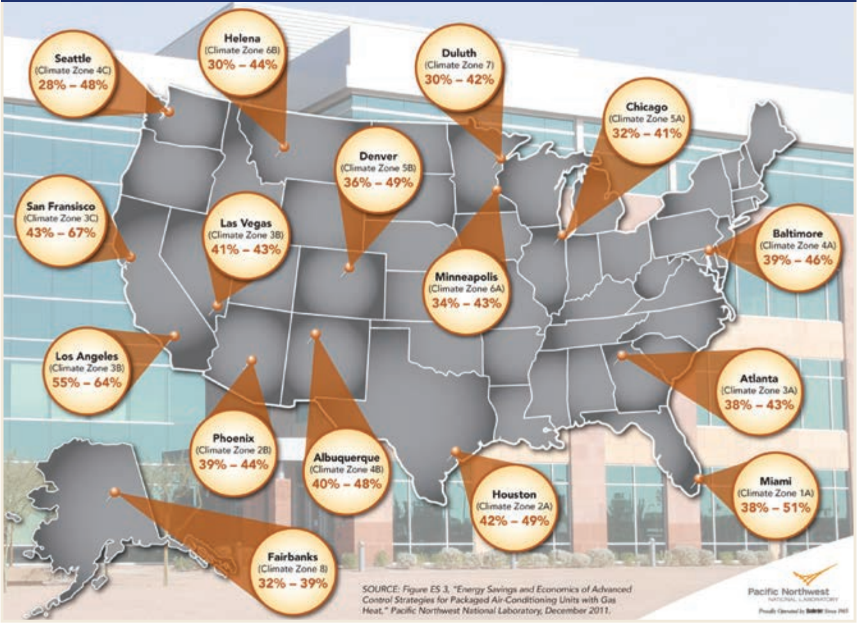
outdoor-air intake and the associated energy needed to condition that air. This strategy reduces the heating and cooling energy, but the supply fan still runs at full speed.

Supply fan energy savings can be achieved by modulating the supply fan speed based on RTU operating mode. When the RTU is in the ventilation mode, the supply fan can run at a lower speed and still provide sufficient fresh air to the space it serves. ASHRAE Standard 90.1-2010 allows for this type of fan airflow control with a single zone variable-air-volume system. Therefore, modulating the supply fan in conjunction with DCV will not only reduce the heating and cooling energy but also reduce the supply fan energy. The total savings (fan and coil) depends on many factors including control strategies, thermostat setpoints and characteristics (throttling range and dead band), oversizing of the packaged unit, and the thermal load profiles.

FIGURE 1 HVAC energy cost savings from use of the integrated differential enthalpy economizer, multi-speed supply-fan control, two-stage capacity control and DCV relative to and as a percentage of the base case (no economizer and constant-speed supply fan) HVAC energy use for 4 building types at 16 climate locations.



SOURCE: *Figure ES 3, "Energy Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat." Pacific Northwest National Laboratory, December 2011.*

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Research, Development & Deployment of Advanced RTU Controls

Pacific Northwest National Laboratory (PNNL) with support from the Department of Energy's (DOE's) Building Technologies Office (BTO) and Bonneville Power Administration (BPA) conducted a multiyear research, development and deployment project to determine the magnitude of energy savings from retrofitting existing RTUs with advanced control strategies not ordinarily used in RTUs.

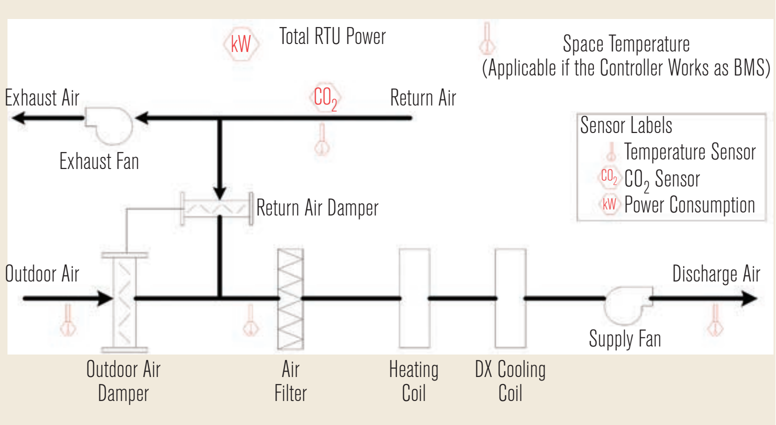
In fiscal year 2011 (FY11), PNNL estimated the potential energy and cost savings from the widespread use of advanced control strategies with RTUs. For that study, the savings were estimated based on detailed EnergyPlus[5] simulation. The major parameters considered in the simulation included four building types, 16 building locations, and 22 combinations of control strategies. The study was limited to air conditioners with gas furnaces.[6] The simulation results showed significant energy savings (between 24% and 35%) and cost savings (between 28% and 67%) from fan, cooling and heating energy consumption when RTUs are retrofitted with advanced control strategies (*Figure 1*).

In FY12, the simulation analysis was extended to packaged heat pumps, but the analysis was limited to two building types, 11 climate locations and eight combinations of control strategies.[7] The simulation analysis showed that combining multispeed fan control and DCV results in energy savings between 37% and 51% across 11 locations for retail buildings and between 25% and 57% for office buildings. Adding an integrated economizer on top of other controls has much smaller marginal impact on energy and cost savings.

Because the simulation analysis showed significant savings from advanced controls retrofits, DOE and BPA decided to fund an extensive field evaluation. In FY12 and FY13, a total of 66 RTUs on eight different buildings were retrofitted with a commercially available advanced controller to improve RTU operational efficiency. Of the 66 RTUs, 17 are packaged heat pumps and the rest are packaged air conditioners with gas heat.

The eight buildings cover four building types, including mercantile (both retail and shopping malls), office, food sales, and healthcare. These buildings are located in four climate zones, including warm and coastal climate (3B), mixed and humid climate (4A), mixed and marine climate (4C), and cool and humid climate (5A). Data at one-minute intervals was collected from these 66 units for a 12-month period. During the monitoring period, the RTU controls were alternated between the standard (pre-retrofit mode) and the advanced control modes on a daily basis. The remainder of the article summarizes the results from the field study. More details on the field study can be found in Wang, et al.[8]

FIGURE 2 Schematic diagram showing sensors used to measure critical parameters in the field test.



Standard Controls and Advanced RTU Controller Description

Before the RTU controller retrofits, all 66 units in the field used "standard" conventional control strategies: the supply fan ran continuously at full speed when the building was occupied; the economizer used a fixed dry-bulb high-limit of 55°F (12.8°C), and it was not integrated with mechanical cooling; and DCV was not used.

In contrast, the advanced off-the-shelf controller tested in the field had these features: integrated differential dry-bulb economizer, supply fan speed control and DCV. It was possible to modulate the supply fan speed because as part of the controller installation, a variable-frequency drive (VFD) was also installed. The supply fan speed was modulated based on the operation mode. In ventilation mode, it was set at 40%, while it was either 75% or 90% during cooling and heating. For DCV, the advanced controller used the return air CO_2 concentration as the trigger to regulate the outdoor air damper and fan speed controls to ensure that the maximum allowable CO_2 level (high CO_2 setpoint = 1,000 ppm) was not exceeded.

Field Measurement, Metering and Monitoring

The advanced controller was tested on 66 RTUs using the same metering and monitoring plan on all units to verify the operations of the advanced controller, estimate the energy savings resulting from retrofitting the RTUs with the advanced controller and estimate of simple payback periods.

A thermistor-type temperature sensor was used to measure outdoor-, return-, mixed-, and discharge-air temperatures, as shown in *Figure 2*. The total true power consumption of the RTU was measured using a power transducer. The CO_2 concentration in the return air duct was monitored using a CO_2 sensor.

Control signals were also monitored (damper, cooling status, heating status, fan speed, etc.). The monitoring plan consisted of data collection at each RTU at one-minute intervals, aggregating the data from all RTUs on a site, storing it locally, and streaming the data in real time to the cloud for analysis.

The advanced RTU controller had a "soft" service switch to change the RTU control logic between the standard (conventional) control and the advanced energy saving control. During the field tests, the standard control and the advanced control were alternated daily for more than 12 months for most units. The standard control was intended to emulate the RTU operation before retrofitting the controller.

Energy Savings Estimation Methodology

The methodology used to estimate the energy savings was similar to that defined in ASHRAE Guideline 14-2002, *Measurement of Energy and Demand Savings*. First, based on the measured energy consumption data during the pre-retrofit period (standard controls) and the post-retrofit period (advanced controls), regression models were developed to correlate the daily RTU energy consumption with the average outdoor air temperature. Then, the pre-retrofit regression model was used under the post-retrofit conditions (post-retrofit outdoor air conditions) to estimate the projected energy consumption in the "standard" control mode. The actual energy savings was computed as the differences between the projected energy use and the measured actual energy use over the same post-retrofit period. In addition to the actual savings, normalized annual savings were also calculated. For this purpose, the pre- and post-retrofit models were used to estimate the pre- and post-retrofit energy consumption using typical meteorological year (TMY) weather data. The difference between the estimated pre- and post-retrofit energy consumption is the normalized annual energy savings.

FIGURE 3 Frequency distribution of actual and normalized RTU electricity savings.

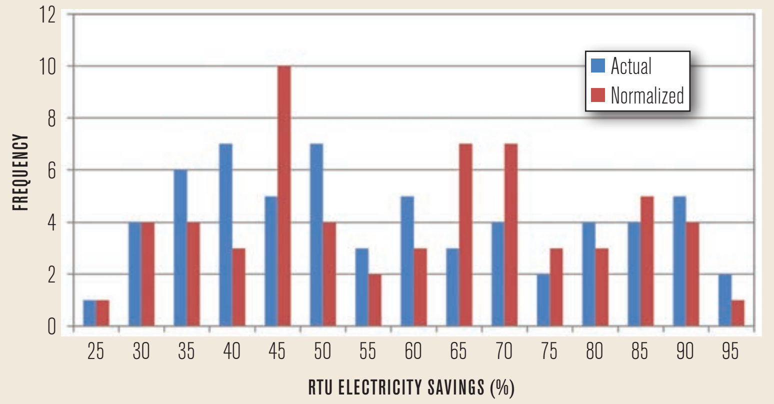
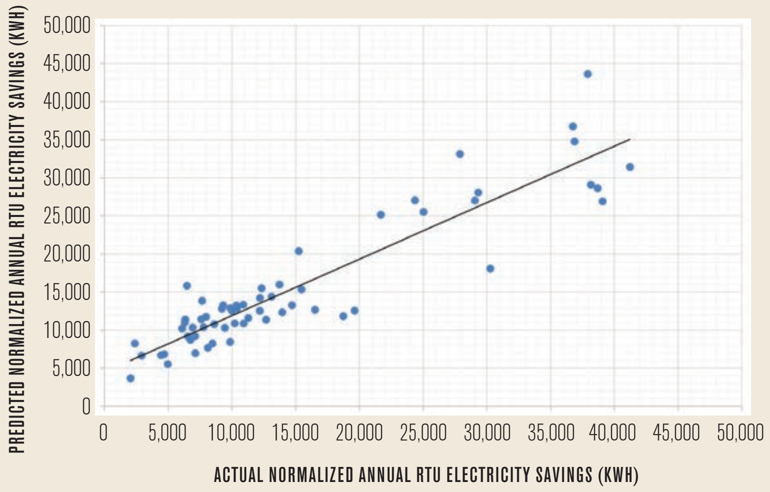


FIGURE 4 Predicted versus actual normalized annual RTU electricity savings.



Because of errors in measurements (i.e., temperature sensors and power meters) and also errors associated with the regression models, the fractional savings uncertainty, expressed as the ratio of the expected savings uncertainty to the total savings, was estimated for both the actual savings and the normalized savings. ASHRAE Guideline 14 was closely followed for the uncertainty calculation.

Summary of Energy Savings Analysis

The majority of savings ranged between 25% and 90% as shown in the frequency distribution plot in *Figure 3*. Because the electricity savings mostly came from fan energy reduction, the units with lower savings usually had longer compressor runtimes while the units with higher savings had shorter compressor runtimes. At 95% confidence level, the fractional uncertainty for actual RTU electricity savings ranged between 2% and 77%, with an average of 22%. The fractional uncertainty for normalized RTU electricity savings ranged between 1% and 51%, with an average of 12%.

The uncertainties were much smaller than the maximum level of uncertainty (i.e., 100% at 95% confidence level) required to meet ASHRAE Guideline 14. The trend was consistent with both air conditioners and heat pumps; therefore, no distinction will be made between the two products. More detailed information specific to the heat pumps is provided in report.[8]

In addition to the percentage of RTU electricity savings, review of the absolute savings would also be useful in understanding the impact of the advanced controller. The variables that had significant effect on the savings included: building type (static pressure and occupancy variations), climate location, fan runtime and the supply-fan motor size. As expected, both actual and normalized savings increased with the RTU size. The normalized savings ranged between 0.47 kWh/h (kWh per fan runtime) and 7.21 kWh/h, with an average of 2.39 kWh/h.

The electricity savings increased from about 1 kWh/h for the group with RTU cooling capacity of less than 10 tons, to 1.8 kWh/h for the group with RTU cooling capacity between 10 and 15 tons (35 and 53 kW), and then to 4.2 kWh/h for the group with RTU cooling capacity greater than 15 tons (53 kW). The normalized electricity savings ranged between 218 Wh/h·hp (292 Wh/h·kW) (Wh per unit fan runtime and per fan motor power) and 1,086 Wh/h·hp (1456 Wh/h·kW) with an average of 695 Wh/h·hp (932 Wh/h·kW), while the fan only electricity savings ranged between 201 Wh/h·hp (269 Wh/h·kW) to 929 Wh/h·hp (1245 Wh/h·kW) with an average of 595 Wh/h·hp (798 Wh/h·kW).

Because the fan runtime and the fan motor size were the dominant contributors to the magnitude of the electricity savings from the RTU controller retrofit, a multiple linear regression with these two parameters as independent variables was conducted. *Figure 4* shows the predicted versus actual annual normalized electricity savings for the RTU and the fan, respectively. The predicted savings were computed using a multiple linear regression with fan runtime (annual run hours) and fan horsepower as independent variables (*Equation 1*). Based on the regression statistics (adjusted R-Squared of 0.922), it appears fan runtime and fan horse power values were good predictors of the potential energy savings from the advanced RTU controller retrofit. Note that for this analysis, fan horsepower was actually measured and the nameplate reading was not used. Using the nameplate reading will introduce some uncertainty but could still be valid.

$$\text{Annual Electricity Savings (kWh)} = 0.382 \times \text{Fan Runtime} + 3{,}688 \times \text{Fan Horsepower} \qquad (1)$$

Payback Analysis

TABLE 1 Advanced RTU controller costs.

RTU CAPACITY (TONS)	SUPPLY-FAN SIZE (HP)	CONTROLLER ($)	CONTROLLER LABOR ($)
≤5	1	2,200	750
>5 AND ≤10	2	2,600	750
>10 AND ≤15	3	3,500	750
>15 AND ≤20	5	4,000	750
> 20 AND ≤25	7.5	4,142	750

The simple payback analysis helps building owners understand the financial impact of RTU controller retrofits and justify their investment. *Table 1* provides the costs associated with the advanced controller retrofit for a single RTU at varying capacities and corresponding supply fan sizes. The controller cost varied because the size of the VFD depended on the size of the supply fan motor, which was included in the controller cost. Labor rate was assumed to be $125/hour. This may vary based on market conditions.

Based on the costs outlined in *Table 1,* a simple payback period was calculated for the advanced controller, based on the projected normalized annual energy savings. Three utility rates were used: $0.05/kWh, $0.10/kWh and $0.15/kWh. Across all units, the annual average cost savings were $744, $1,489 and $2,233 for the three considered utility rates, with a corresponding average installed cost of $4,172, resulting in average payback period of six, three, and two years, respectively. Wang, et al.,[8] provides additional details on the payback period calculation accounting for the metering and monitoring packages.

For individual units, the simple payback period varies from nine months to 10 years at a utility rate of $0.15/kWh. This variation in payback period largely depends on RTU size and RTU runtime. The units with the shortest payback period were either large units (e.g., greater than 15 tons [53 kW]) or had the longest annual runtime (operating hours per year).

Figures 5 and *6,* on the other hand, show the average payback period for varying utility rates and three different utility incentive scenarios. These units had varying capacities (between 5 and 25 tons [18 and 88 kW]) and varying annual runtimes (between 4,004 and 8,736 hours). As you can see, for units smaller than 10 tons (35 kW), the average payback period was three years or less for utility rates above $0.12/kWh when incentives were offered (three years at 25% incentives and two years at 50% incentives, respectively), and $0.16/kWh without incentives.

For units larger than 15 tons (53 kW) (*Figure 6*), the average payback period was less than three years, with or without incentives. Although not shown in either figure, for units between 10 tons (35 kW) and 15 tons

FIGURE 5 Average payback period for units with capacities less than 10 tons (35 kW), for varying runtimes and utility rates.

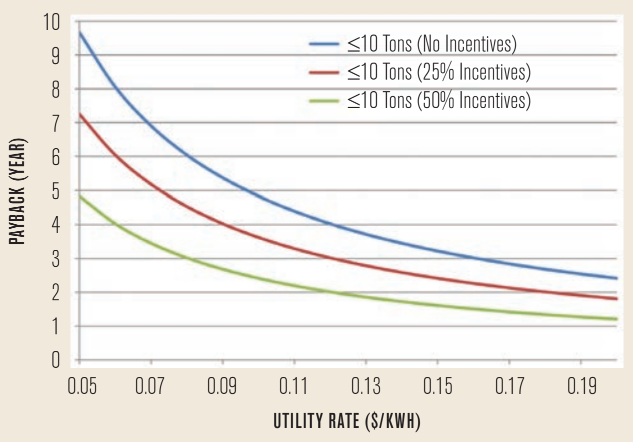


FIGURE 6 Average payback period for units with capacities greater than 15 tons (53 kW), for varying runtimes and utility rates.

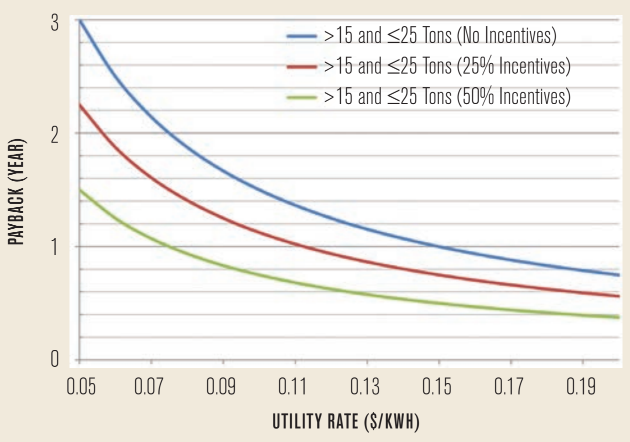


TABLE 2 Recommendations on when to consider advanced RTU control retrofit that yield less than three-year payback.

RTU SIZE	AVERAGE RUN HOURS PER DAY	UTILITIES RATES AND INCENTIVES
>20 TONS	>14	At Any Utility Rates and With No Incentive
>20 TONS	12 to 14	\$0.10/kWh With No Incentive
>20 TONS	<10	\$0.10/kWh With Moderate (25%) Incentive
15 TO 18 TONS	>14	\$0.12/kWh With No Incentive
15 TO 18 TONS	<10	\$0.10/kWh With High (50%) Incentive
7.5 TO 12.5 TONS	>14	\$0.15/kWh With No Incentive
7.5 TO 12.5 TONS	<10	\$0.15/kWh With High (50%) Incentive
>7.5 TONS	>14	\$0.10/kWh With High (50%) Incentive
>7.5 TONS	>14	\$0.12/kWh With Moderate (25%) Incentive
>7.5 TONS	<10	\$0.15/kWh With High (50%) Incentive

(53 kW), the average payback period was three years or less for utility rates above \$0.09/kWh when incentives were offered (3.1 years at 25% incentives, and 2.1 years at 50% incentives, respectively), and \$0.12/kWh without incentives.

The payback results prove that, on average, a unit smaller than 15 tons (53 kW) requires some sort of incentive when installing the advanced controller to obtain a payback period of less than three years, or be located in a place with a utility rate of \$0.12/kWh or greater. However, if the unit was larger than 15 tons (53 kW), the payback period will always be less than three years, with or without incentives being offered.

Recommendations on When to Consider the Retrofit

Based on the analysis of 66 units in four different building types and four climate locations, it is clear that the building type, unit runtime and supply-fan motor size are significant contributors to the energy savings potential. Although savings associated with DCV were expected to be high in extreme climate locations, most of the climate locations in the study are not extreme. Consider retrofitting an existing RTU with advanced controller under the conditions outlined in *Table 2*, which will yield a three-year payback period.

The previous rules-of-thumb can be used for screening purposes, but a more thorough analysis based on site-specific conditions may be necessary. For units that are 5 tons (18 kW) and smaller, which typically use single-phase fan motors, this technology is not going to be cost effective; however, there are other options for those units with single-phase motors that are cost-effective. Those options were not considered in this study.

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