Including Economizers in the Unitary Next-Generation Test Procedure Standards

Peter Jacobs, P.E., Building Metrics Inc.
Robert Mowris, P.E., Verified Inc.

ABSTRACT

Including economizers in unitary next-generation test procedure standards will improve thermal comfort, indoor air quality, and energy efficiency. Currently, no laboratory test standards exist for air-side economizers when installed on commercial Heating, Ventilating, and Air Conditioning (HVAC) equipment. Research studies indicate that 50 to 70% of economizers do not function properly which reduces comfort and increases energy use by 18 to 37%. Most economizers provide excess outdoor airflow at minimum or closed damper positions and insufficient outdoor airflow at fully open damper positions during economizer cooling which increases energy use. To address these issues, the California Energy Commission (CEC) building energy efficiency standards require fault detection diagnostic systems to check economizer operation on commercial HVAC systems. The CEC standards and supporting studies are based on building energy simulation models which assume perfect outdoor airflow, perfect integrated economizer plus mechanical cooling, no thermostat or economizer delays or dead bands, and no unoccupied fan operation. An economizer test procedure is needed to understand how to improve economizer efficiency and how economizers interact with mechanical cooling systems. This paper provides field and laboratory test results for technologies to improve economizer efficiency and a proposed economizer test procedure to be included in the unitary next-generation test procedure standard. Potential energy savings for the economizer efficiency test standard are 21% for cooling plus fan and 18% for heating. This is equivalent to about 1% of total US energy consumption. The simple payback is 2.2 years based on a cost of $0.19/ft^2 and savings of $0.09/ft^2-yr.

Introduction

Commercial HVAC accounts for 18% of peak electricity demand and consumes about 5.9% of total annual energy use in the United States (US) according to the US Energy Information Administration (EIA 2019). Commercial cooling uses 32.1% of total annual US HVAC energy, heating uses 33.9%, and ventilation uses 34% due to continuous or hourly fan operation (EIA 2019). Packaged roof-top units (hereafter "units") serve over 60% of the commercial floor area in the US (EIA 2019). Most packaged units have an airside "economizer" to provide a maximum Outdoor Airflow (OA) for economizer cooling when the outdoor air temperature (OAT) is less than a high-limit shut-off temperature (HST) minus a 1 to 2-degree Fahrenheit (F) dead band. If the OAT is greater than or equal to the HST, then space cooling is provided by direct expansion (DX) Air Conditioning (AC) compressors, and the economizer provides a minimum outdoor airflow to meet indoor air quality (IAQ) requirements per the American National Standards Institute (ANSI) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1 (ANSI/ASHRAE 2019).[1] Research

[1] Air-side economizers have movable metal outdoor-air and relief-air dampers with gears controlled by an actuator mounted in a metal frame installed in a HVAC system cabinet. Actuator control voltage ranges from 2 to 8 volts (V) with 2V offset. Closed position is 2V, 20% minimum is 3.6V (0.20 × 8V+ 2V), and fully open is 10V (8V + 2V).

studies show that 50 to 70% of existing commercial air-side economizers in the US are not functioning properly and FDD controls can improve cooling efficiency by 18 to 37% or more (Jacobs 2003; Cowan 2004; Hart 2006; Heinemeier 2018).[2] A 2010 study published by ASHRAE recommended changes to the ANSI/ASHRAE Standards 90.1 and 189.1 with respect to the air-side economizer HST control settings (ANSI/ASHRAE 2013, 2017; Taylor 2010). The 2013 ASHRAE 90.1 standard requires economizer demand control ventilation (DCV) and 70 to 75F HST control settings in California climates zones.[3] A 2011 study published by Pacific Northwest National Laboratories (PNNL) reported cooling and heating savings of 24 to 32% for small office, retail, and supermarket buildings with economizer DCV and multi-speed supply fans (Wang 2011). To address these issues, the California Energy Commission (CEC) 2016 building energy efficiency standards adopted the 69 to 75F HST control settings per ASHRAE 90.1, economizer DCV, and FDD to check economizer operation and excess outdoor airflow (CEC 2015). The ASHRAE Standard 207P provides methods for laboratory testing of FDD systems for damper operation to determine whether they perform as specified, but 207P does not provide performance standards for economizers installed on packaged units (BSR/ASHRAE 2020).

ASHRAE and the US Green Building Council (USGBC) are developing a Load-Based Testing Approach for a Next-Generation Equipment Rating. ASHRAE Standard 221-2020 provides a test method to field-measure and score the cooling and heating performance of an installed unitary HVAC system. While these standards are designed to enable technicians to score and quantify the efficiency and capacity of an HVAC system in the field, they do not include methods for testing the performance of packaged units with economizers. The ASHRAE Guideline 1.7P Ongoing Commissioning Process defines best practices for conducting Building Commissioning (BCx) beyond the minimum practices required to satisfy codes and standards (BCR 2019). However, there are no specific economizer efficiency standards or laboratory test procedures to define best practices.

This paper provides field and laboratory test results and information to include economizer efficiency in the unitary next-generation test procedure standards such as ASHRAE 221, ASHRAE 240/210, and ASHARAE 340/360 (ASHARE 2019, ASHRAE 2020). Economizer efficiency needs to be included in the California building energy efficiency standards to bring actual performance closer to the idealized performance predicted by DOE-2.2 and EnergyPlus simulation models (Crawley 2000, Mowris et al. 2020, 2021, 2021a, 2021b).

Definition

An **air economizer** comprises an outdoor and return damper assembly controlled by a thermostat, a controller, sensors, and an actuator to perform the following functions. **(1)** Modulate outdoor airflow and return airflow to provide a maximum amount of outdoor airflow for cooling with only a ventilation fan when outdoor airflow can meet a cooling load by itself.[4] **(2)** Provide the maximum amount of outdoor airflow for cooling with an integrated mechanical cooling system when outdoor airflow can only meet part of the cooling load.[5] **(3)** Reduce outdoor airflow to the

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[2] Faults include: 1) air temperature sensor failure/fault, 2) not economizing when should, 3) economizing when should not, 4) damper not modulating, 5) excess outdoor airflow, and 6) other issues (CEC 2018 and ibid).

[3] Demand controlled ventilation (DCV) automatically adjusts economizer damper position and outdoor air airflow in response to changes in occupancy or carbon dioxide (CO2) concentrations.

[4] ASHRAE 90.1 6.5.1.1.1 and ASHRAE Terminology. CA Title 24, Part 6 §140.4(e)1.

[5] ASHRAE 90.1 Section 6.5.1. Section 6.5.1 Economizers (pp. 50-51). Integrated Economizer Control. CA Title 24, Part 6 §140.4(e)2.

design minimum to meet indoor air quality requirements when outdoor airflow is unable to reduce cooling energy use and cooling is only provided by the integrated mechanical cooling system.[6] **(4)** Avoid increased heating energy use during normal operation.[7] **(5)** Detect and report economizer sensor and damper position faults.[8]

Proposed Economizer Efficiency Standard

The economizer efficiency standard test setup includes a digitally controlled damper assembly installed on the return duct to provide negative inlet static pressure (ISP) and external static pressure (ESP) similar to in-situ conditions. Controlling inlet and total static pressure provides realistic test conditions to measure performance when varying airflow, fan speed, and economizer outdoor-air damper positions from closed to fully open. Economizer efficiency "E" tests will be performed with at least three damper positions: closed, intermediate (10, 20, or 30% OA), and fully open. The outdoor airflow at each damper position will be reported since most economizers are unable to provide 100% OA when fully open or 0% OA when fully closed. The proposed indoor and outdoor test conditions for economizer-only cooling, integrated cooling (economizer plus mechanical), and mechanical-only cooling will harmonize with existing standards for fixed drybulb, differential drybulb, and enthalpy controls.[9] The proposed test procedure will provide an economizer "E" rating at each temperature and damper position to indicate how economizer, integrated, and mechanical cooling efficiency are impacted by economizer outdoor airflow, calibration, and controls. The economizer efficiency test will encourage the following performance criteria: 1) minimize excess OA and maximize economizer cooling OA; 2) continuous calibration to verify the minimum and maximum outdoor airflow fractions (OAF) and damper positions; 3) ensure economizer cooling occurs with outdoor dampers fully open and return dampers fully closed when OAT is less than or equal to 63F; and 4) ensure integrated economizer plus mechanical cooling occurs when the OAT is greater than 63F and less than a High Shut-off temperature (HST) as shown in Table 1 (ASHRAE 2013, CEC 2016).

Table 1: Air economizer high-limit shut-off temperature fixed dry bulb control requirement

CA T-24 Climate zone	**High-limit Shut-off Temperature**	**Required high limit (economizer off when)**
1, 3, 5, 11-16	OAT > 75F	Outdoor air temperature exceeds 75°F
2, 4, 10	OAT > 73F	Outdoor air temperature exceeds 73°F
6, 8, 9	OAT > 71F	Outdoor air temperature exceeds 71°F
7	OAT > 69F	Outdoor air temperature exceeds 69°F

The Economizer efficiency standard will encourage methods to improve efficiency by: 5) detecting thermostat cooling delays when the economizer cannot satisfy the call for cooling and supersede thermostat second-stage time and/or temperature deadband delays to fully open dampers and simultaneously energize AC compressor(s) during integrated economizer cooling; 6) detecting and overriding economizer second-stage delays to energize first-plus-second-stage

[6] ASHRAE 90.1 Section 6.5.1.1.3 and ASHRAE 62.1 Section 1.1 High-Limit Shutoff.
[7] ASHRAE 90.1 6.5.1.5 and Fundamentals Chapter 16. Economizer Heating System Impact. CA Title 24, Part 6: §140.4(e)2.
[8] ASHRAE 207P. CA Title 24, Part 6 §120.2(i)
[9] ASHRAE 2013. P. 50-51. Table 6.5.1.1.3 High-Limit Shutoff Control Settings for Air Economizers. CEC 2016. p. 190. Table 140.4-B Air Economizer High Limit Shut Off Control Requirements

AC compressors when thermostat energizes second-stage cooling to increase mechanical cooling efficiency; and 7) enabling economizer cooling otherwise delayed by HST deadband unless OAT is less than or equal to HST minus 2F (or OAT ≤ HST minus 1F).

Test Data to Support the Economizer Efficiency Standard

The economizer efficiency standard is supported by cooling and heating energy savings based on field tests and third-party laboratory tests performed by Intertek, an ISO-certified laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with Federal energy efficiency standards (GAO 1975). Laboratory tests were performed on four new packaged HVAC units with DX Air Conditioning (AC) compressors and economizers. The following four packaged units were tested at Intertek: 1) 7.5-ton two-compressor non-TXV unit #1, 2) 7.5-ton two-compressor TXV unit #2, 3) 3-ton non-TXV unit #3, and 4) 3-ton TXV unit #4.[10] Field tests were performed on a 10-ton two-compressor packaged unit #8 installed on a commercial office building located in Reno, Nevada.

The Intertek test facility consists of climate-controlled indoor and outdoor chambers where HVAC systems and measurement equipment are assembled and installed by laboratory technicians. Cooling verification tests were performed according to the AHRI Standard 210/240 2017 and AHRI Standard 340/360 2019 (AHRI 2019). Economizer airflow tests were performed according to ANSI/ASHRAE 41.2-1987 Standard Methods for Laboratory Airflow Measurement (ANSI/ASHRAE 1987). Thermal efficiency tests were performed according to ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006 (ANSI/CSA 2006). Laboratory test equipment was calibrated per ISO 17025 by an accredited provider per the International Laboratory Accreditation Cooperation (ILAC) (ISO 2017).

Laboratory Tests

Laboratory and field tests were performed under steady-state conditions to measure base and economizer cooling capacity, efficiency, and OAF for a range of economizer actuator control voltages and damper positions (RMA 2016). Figure 1 shows laboratory tests of damper position OAF (y) versus economizer actuator control voltage (x) for unit #3 with the base economizer and the calibrated economizer with sealed perimeter gap. The base economizer controller assumes OAF is proportional to economizer actuator voltage (x) where the closed position provides 0% OAF and the fully open provides 100% OAF. Sealing the gap reduces outdoor airflow by 9.5% from 23.5% to 14% at the 2V closed damper position, but only reduces outdoor airflow by 0.5% from 66.3 % to 65.5% at the 10V fully open position (with return gap unsealed). If both economizer supply and return perimeter gaps are sealed, then outdoor airflow at the fully open damper position might increase compared to unsealed. This was not tested. The base economizer provides 27.2% outdoor airflow at 3.6V ($0.2*8V_{range} + 2V_{offset} = 3.6V$), and the calibrated economizer with sealed perimeter gap provides 20% OAF at 3.64V with potential peak capacity savings of 7.2%. Based on laboratory tests of four packaged HVAC units, the average outdoor airflow at the fully open economizer cooling damper position is 66% ± 5% indicating 34% less economizer cooling than assumed by building energy simulation programs.

[10] One ton of cooling equals 12,000 British thermal units per hour (Btu/hr)

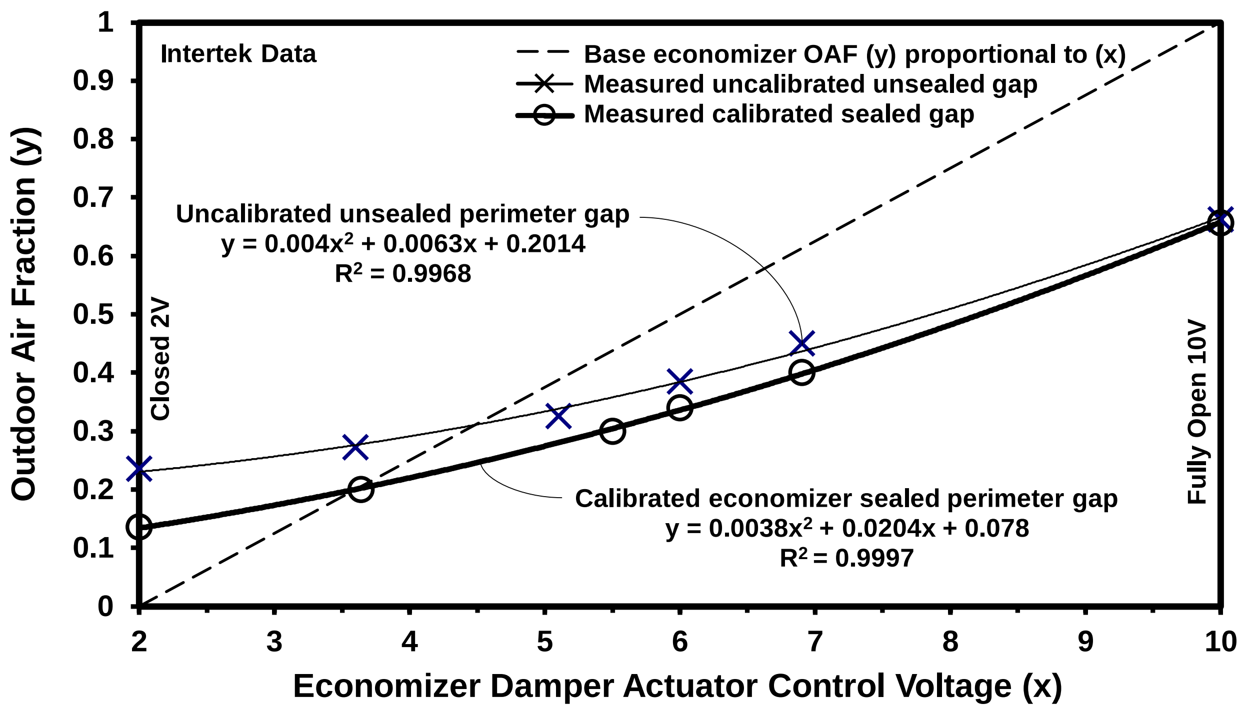

Figure 1. Laboratory tests Unit #3 base economizer and calibrated economizer with sealed perimeter gap

Sealing the economizer perimeter gap between the economizer frame and the HVAC system cabinet reduces uncontrolled excess outdoor airflow (Mowris 2021). The economizer calibration method provides a functional relationship between the actuator voltage (x) and a corresponding damper position OAF (y) (Mowris 2021a). The method measures x- y data at a closed damper position, at least one intermediate position, and a fully open position. Coefficients are calculated using the x-y data. The target actuator voltage (x_t) is calculated using the functional relationship and a required OAF (y_r) based on building occupancy per ASHRAE 62.1 (ANSI/ASHRAE 2019). Target actuator voltage is at the minimum position.

The following equations shown in Figure 1 provide the functional relationship between the economizer actuator voltage (x) and the corresponding OAF (y) for the unsealed and sealed economizer perimeter gap.

Eq. 1 $y_{base} = 0.004\, x_i^2 + 0.0063\, x_i + 0.2014$

Where, y_{base} = base OAF (dimensionless), and
x_i = base economizer actuator voltage from 2V to 10V (Volts).

Eq. 2 $y_c = 0.0038\, x_i^2 + 0.0204\, x_i + 0.078$

Where, y_c = calibrated OAF with sealed perimeter gap (dimensionless), and
x_i = calibrated economizer actuator voltage from 2V to 10V (Volts).

Table 2 provides AHRI Energy Efficiency Ratio (EER) ratings and laboratory test data for two 7.5-ton units and two 3-ton units with and without an economizer, closed and minimum damper positions (e.g., 3-fingers open base and 30% calibrated minimum), unsealed and sealed perimeter gap. Tests were performed at typical field conditions and external static pressures which are different than ANSI/AHRI 340/360 or 210/240 conditions.[11] The average AHRI EER rating is 11.1 for all units. The average tested EER* is 8.7 with no economizer or 21% less than average AHRI ratings. The average EER* is 6.9 with dampers closed or 38% less than AHRI ratings. With sealed perimeter gap average efficiency is 7.7 EER* or 31% less than rated. The average EER* is 4.2 with economizer dampers at minimum position unsealed (3-fingers open) or 62% less than average AHRI ratings.[12] With the economizer supply damper perimeter gap sealed and calibration to 30% minimum OAF, average efficiency is 5.8 EER* which is 48% less than the average AHRI rating. The EER* improvement for economizer perimeter gap sealing and calibration is 38% indicating a need to test units with economizers installed. The average outdoor airflow is 18.1 ± 4% at closed damper positions and 41.2 ± 5.2% at uncalibrated minimum damper positions. The average OAF is 35.2 ± 7.6% at 4.4V or 30% actuator position with the gap unsealed which is close to the 3-F setting. Two units provided less than 30% OAF at 4.4V which would impact indoor air quality. Building designers and simulation programs assume 0% OAF at closed damper positions and the recommended minimum OAF based on building occupancy per ASHRAE 62.1.

Table 2: AHRI Ratings and Laboratory Test Data for 7.5-ton and 3-ton units with and without an Economizer, closed and minimum damper positions, unsealed perimeter gap and calibration at 95F

Unit	AHRI EER Rating	No Econo EER*	No Econo OAF	Unseal Econo closed damper EER*	Unseal Econo closed damper OAF	Seal gap closed damper EER*	Seal gap closed damper OAF	Unseal gap Econo 3-F open EER*	Unseal gap Econo 3-F open OAF	Calib + seal gap Econo 30% OA EER*
7.5-ton non-TXV	11	7.6	6.0%	5.7	16.7%	6.3	13.4%	3.4	37.1%	4.9
7.5-ton TXV	11	8.8	5.7%	7.6	12.1%	7.9	8.2%	5.3	39.0%	7
3-ton non-TXV	11	9.2	2.0%	6.4	23.5%	7.9	14.0%	4.1	50.6%	5.5
3-ton TXV	11.2	9.1	3.9%	7.7	19.9%	8.6	12.3%	4.1	38.2%	5.8
Average	**11.1**	**8.7**	**4.4%**	**6.9**	**18.1%**	**7.7**	**12.0%**	**4.2**	**41.2%**	**5.8**
Average Impact		**-21%**		**-38%**		**-31%**		**-62%**		**-48%**

Table 3 provides Intertek laboratory tests of unit #1 with and without economizer or compressors when occupied. The nominal AHRI rating is 11.0 EER for unit #1 and the rated sensible efficiency is 7.7 EER. Tested sensible EER* values are lower than rated values due to the test procedure at different conditions, not including outdoor airflow with an economizer, and only providing performance data for two-stage compressor operation.

[11] ANSI/AHRI 340/360 and 210/240 test conditions are 80F DB and 67F WB indoor and 95F OAT and 0.25 IWC ESP for 7.5-ton units and 0.15 IWC for 3-ton units. Tests in the table were performed at typical field conditions of 75F DB and 62F WB indoor and 95F OAT and ESP of 1.1 to 1.2 IWC for 7.5-ton non-TXV, 0.6 to 0.9 IWC for 7.5-ton TXV, 0.5 to 0.6 IWC for 3-ton non-TXV, and 0.7 IWC for 3-ton TXV.

[12] Technicians use 1-finger (1-F) for 10% open, 2-F for 20% open, 3-F for 30% open dampers, and 3-F provided 41% minimum OA.

Table 3. Laboratory tests of unit #1 with and without economizer or compressors when occupied

Description	OAT (F) [a]	Total Power (W) [b]	Sensible Cooling (Btuh) [c]	Sensible (EER*) [d=c/b]	Economizer Savings (%) [e]	FDD ECDC savings (%) [f]
1st-stage AC compressor	95	5,684	20,485	3.60		
1st + 2nd-stage AC compressors	95	8,987	53,195	5.92		39.1%
1st-stage AC compressor	82	5,103	21,532	4.22		
1st + 2nd-stage AC compressors	82	7,845	52,707	6.72		37.2%
Economizer fan only	70	1,539	5,015	3.26		
Economizer + 1st-stage AC	70	4,586	35,264	7.69		
Economizer +1st+2nd-stage AC	70	6,989	62,863	8.99		14.5%
Economizer fan only	65	1,550	12,989	8.38	-25.3%	
Economizer + 1st-stage AC	65	4,446	43,053	9.68		
Economizer +1st+2nd-stage AC	65	6,651	69,813	10.50		7.7%
Economizer fan only	60	1,585	20,697	13.06	11.5%	
Economizer + 1st-stage AC	60	4,342	49,245	11.34		
Economizer +1st+2nd-stage AC	60	6,341	73,295	11.56		1.9%
Economizer fan only	55	1,583	28,942	18.28	27.3%	
Economizer + 1st-stage AC	55	4,205	55,897	13.29		
Economizer +1st+2nd-stage AC	55	6,052	79,444	13.13		-1.3%

Figure 2 shows the impact of the thermostat second-stage time delay, thermostat dead band delay, and the economizer second-stage time delay which reduce energy efficiency and thermal comfort when the building is occupied.

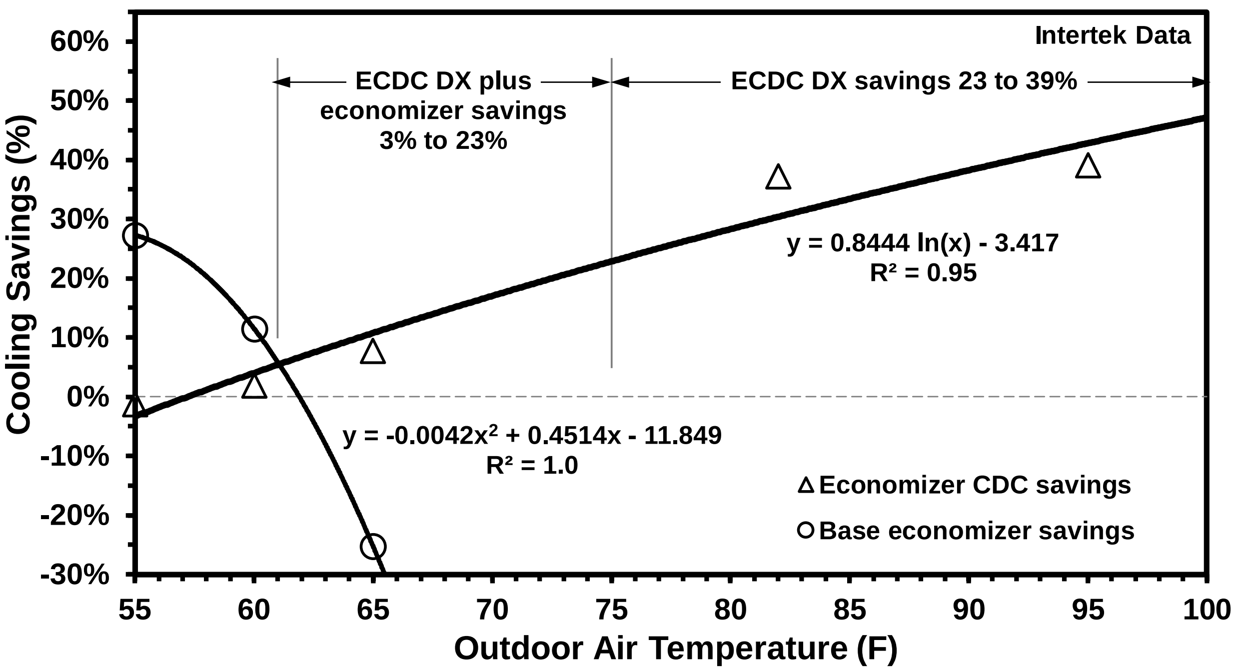

Figure 2. Laboratory tests of economizer cooling delay correction savings vs. OAT when occupied

Figure 2 shows ECDC cooling savings for OAT conditions ranging from 63F to 100F for unit #1 based on data provided in Table 3. Figure 2 shows economizer cooling is only more efficient than ECDC when the OAT is less than 61F which is the default (HST minus deadband) for most economizer controllers. ECDC plus economizer savings are 3 to 23% from 61F to 75F, and savings are 23 to 39% from 75F to 100F. ECDC supersedes: 1) thermostat second-stage time delay which varies from 2 to 60 minutes, 2) thermostat second-stage temperature deadband which varies from 2 to 4F, and 3) default economizer second-stage time delay which varies from 4 minutes (Belimo 2013) to 120 minutes (Honeywell 2014). The ECDC measure is modeled with the DOE-2.2 hourly post-processer and the following equation when OAT is greater than 63F.

Eq. 3 $y = 0.844407 \, LN(x) - 3.417134$

Where, y = ECDC energy savings (dimensionless), and
x = OAT (F) based on the DOE-2.2 hourly data.

Table 3 shows the economizer fan only is more efficient than the economizer plus first-stage AC compressor and first-stage plus second-stage AC compressor at 55F (27.3%) and 60F OAT (11.5%). At 65F and above, the economizer is less efficient. The economizer plus first-plus-second-stage AC compressor is 1.9 to 39.1% more efficient than the first-stage AC compressor at 60F or greater OAT. Economizer Cooling Delay Correction (ECDC) satisfies the thermostat sooner and provides annual cooling savings of 4.9 ± 1.1%. ECDC supersedes thermostat and or economizer second-stage delays and energizes first-plus-second-stage AC compressors when the thermostat energizes the second-stage cooling signal (Mowris 2021b). The ECDC method is more efficient than the first-stage AC compressor for all OAT conditions when internal loads are equivalent to cooling loads.[13]

` Cooling savings are calculated based on superseding the 4-minute time delay (no savings for remaining hour) and the 120-minute time delay (no savings for the hour after each 120-minute time delay) when the PLR is greater than the ratio of the first-to-second-stage cooling capacity (i.e., indicating a thermostat second-stage call for cooling).

Field Tests

Figure 3 provides field tests of the 10-ton unit #8 with base economizer and 63F default HST and the thermostat cooling delay correction (TCDC) (Mowris 2021b). Figure 3 shows the TCDC method improves cooling efficiency for these tests by 32% compared to the base economizer with default 63F HST (Honeywell 2018). Average annual cooling savings for the TCDC are 7.2% ± 2.9% based on DOE-2 simulations discussed below.

[13] Intertek maintained 75F drybulb and 62F wetbulb indoor conditions to emulate an occupied commercial building.

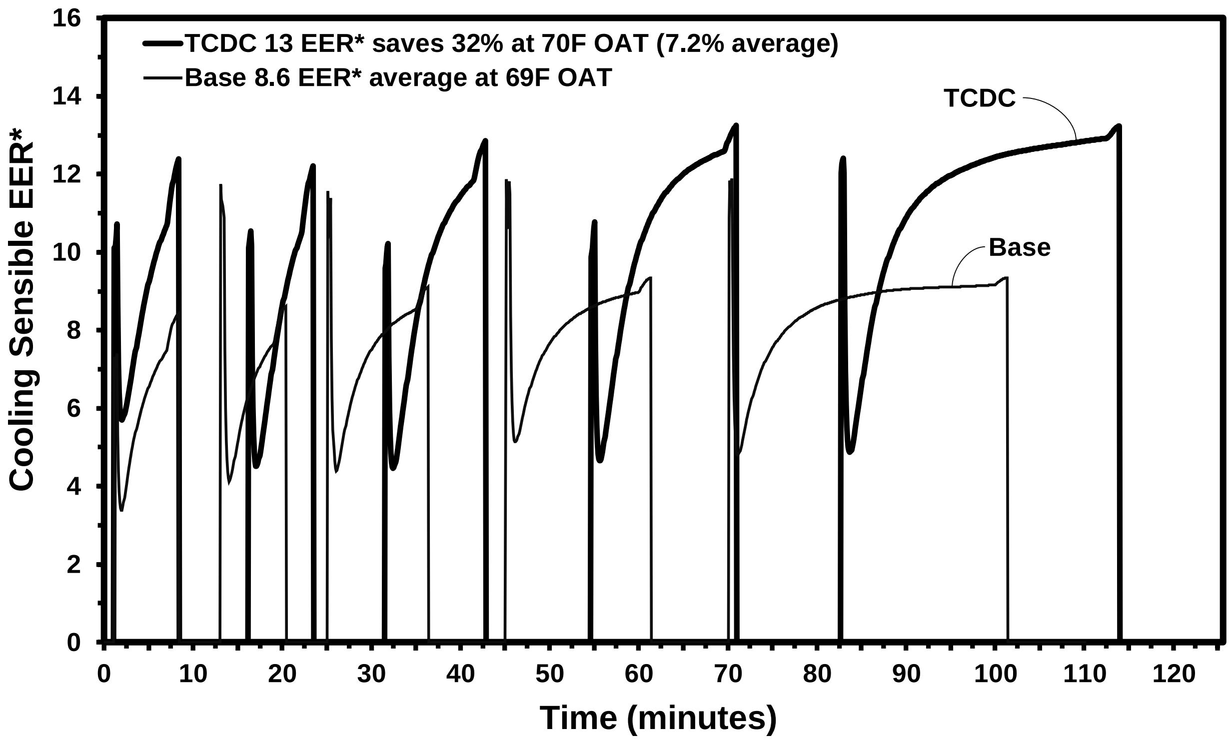

Figure 3. Field tests of Unit #8 thermostat cooling delay correction vs. base economizer

The TCDC fully opens the economizer damper and simultaneously energizes the AC compressor to minimize compressor operation and maximize efficiency and thermal comfort.[14] For this example, the TCDC improves cooling efficiency by 32% compared to the base economizer which closes the damper when the OAT is greater than the default 63F HST (Honeywell 2018). With 75F HST (per CEC 2015) instead of 63F HST, base efficiency would be 6.85 EER with damper fully open and no compressor (or 20% lower than the base 8.6 EER shown in Figure 3).

Currently available "integrated" economizer controllers only energize the AC compressor after the thermostat second-stage Y2 cooling signal is energized. The second-stage Y2 signal is not energized until the thermostat second-stage time delay is exceeded (2 to 60 minutes) or Conditioned Space Temperature (CST) is 3F or more above the cooling setpoint. These delays require about 12.4 to 29.4% more compressor operation (see Table 4 and 5). TCDC savings are calculated using the heat balance equations to determine how much extra compressor energy is required to remove heat from the room air due to the thermostat second-stage delays. TCDC AC control temperature (ACT) is 63F when occupied and 69F when unoccupied.

Eq. 4 $Q_{net} = Q_{sc} + (Q_e + Q_i)$

Where Q_{net} = net DX AC sensible heat removal rate (Btu) [Table 4 or 5 column g],
Q_{sc} = average DOE-2 DX coil sensible cooling (Btu) [Table 4 or 5 column e],
Q_e = average DOE-2 economizer heat removal (Btu) [Table 4 or 5 column b],
Q_i = average DOE-2 sensible heat added to room air (Btu) [Table 4 or Table 4 column c].

The following equation is used to determine the corrected AC power input for each hour.

[14] The CDC control limits are 63F < OAT < HST occupied, and 69F < OAT < HST when unoccupied.

Eq. 5 $e_c = e_{ac}(1 - Q_v/Q_{sc})$

Where e_c = corrected DOE-2 AC power (kWh) [Table 4 or 5 column i],
e_{ac} = average DOE-2 hourly DX AC plus fan power (kWh) [Table 4 or 5 column h],
Q_v = heat added to room air causing 2F CST increase (Btu) [Table 4 or 5 column d].[15]

Eq. 6 $\Delta e_{FT} = 1 - e_{ac}/e_c$

Where Δe_{FT} = TCDC savings when occupied or unoccupied [**Table 4** or **5** column j].

Table 4 provides TCDC savings using these two equations based on occupied DOE-2.2 hourly data. Table 5 provides the calculations based on unoccupied DOE-2.2 hourly data.

Table 4. Thermostat cooling delay correction savings based on occupied DOE-2.2 hourly data

OAT (F) a	**Economizer heat removal Q_e Btu b**	**Sensible load heat Q_i Btu c**	**Room air volume heat Q_v Btu d**	**DX coil sensible cooling Q_{sc} Btu E**	**DX AC PLR f**	**Net DX AC sensible capacity Q_{net} Btu g=e+b+c**	**DOE-2 DX AC e_{ac} kWh h**	**Corrected DOE-2 DX AC e_c kWh i=h*(1-d/g)**	**FDD TCDC savings occupied Δe_{FT} % J=1-h/i**
63	63,302	-61,636	-2,285	3,824	0.02	5,489	0.33	0.46	29.4%
64	57,621	-58,101	-2,285	6,297	0.04	5,816	0.50	0.70	28.2%
65	51939	-56972	-2,285	11529	0.07	6,496	0.94	1.27	26.0%
66	46258	-58755	-2,285	19723	0.11	7,226	1.67	2.19	24.0%
67	40576	-59721	-2,285	27013	0.15	7,868	2.18	2.82	22.5%
68	34895	-56470	-2,285	31190	0.17	9,614	2.43	3.00	19.2%
69	29213	-58713	-2,285	39373	0.21	9,873	3.17	3.90	18.8%
70	23532	-54389	-2,285	41930	0.21	11,072	3.44	4.15	17.1%
71	17850	-54763	-2,285	49015	0.24	12,103	3.63	4.31	15.9%
72	12168	-59245	-2,285	60610	0.29	13,533	4.53	5.29	14.4%
73	6487	-56268	-2,285	64113	0.30	14,331	4.93	5.72	13.8%
74	805	-51190	-2,285	64603	0.31	14,219	5.13	5.96	13.8%
75	-4876	-54363	-2,285	72883	0.34	13,643	5.86	6.84	14.3%

Table 5. Thermostat cooling delay correction savings based on unoccupied DOE-2.2 hourly data

OAT (F) a	**Economizer heat removal Q_e Btu b**	**Sensible load heat Q_i Btu c**	**Room air volume heat Q_v Btu d**	**DX coil sensible cooling Q_{sc} Btu E**	**DX AC PLR f**	**Net DX AC sensible capacity Q_{net} Btu g=e+b+c**	**DOE-2 DX AC e_{ac} kWh h**	**Corrected DOE-2 DX AC e_c kWh i=h*(1-d/g)**	**FDD TCDC savings unoccupied Δe_{FT} % J=1-h/i**
69	29,213	-23,686	-2,285	6,451	0.04	11,978	0.60	0.72	16.0%
70	23,532	-20,638	-2,285	9,606	0.05	12,500	0.88	1.04	15.5%
71	17850	-22049	-2,285	17381	0.09	13,182	1.59	1.86	14.8%
72	12168	-23118	-2,285	24637	0.13	13,687	2.34	2.73	14.3%
73	6487	-21167	-2,285	29737	0.15	15,057	2.75	3.16	13.2%
74	805	-21043	-2,285	36007	0.18	15,770	3.36	3.85	12.7%
75	-4876	-21925	-2,285	42895	0.20	16,095	4.21	4.81	12.4%

Figure 4 provides regression Equation 7 used to calculate TCDC savings when the building is occupied. Figure 4 also provides regression Equation 8 used to calculate the TCDC

[15] Calculated as room volume times air specific heat times air density times 2F thermostat deadband.

savings when the building is unoccupied. The independent variable, x, is the difference between the HST and the OAT which varies from 0 to 12F when occupied and from 0 to 6F when unoccupied. Actual AC energy use will vary depending on OAT conditions, internal loads, thermostat settings (i.e., first and second stage), and system configuration.[16] The TCDC occupied savings are 14.3 to 29.4% (upper curve), and unoccupied savings are 12.4 to 16% (lower curve) depending on HST minus OAT.

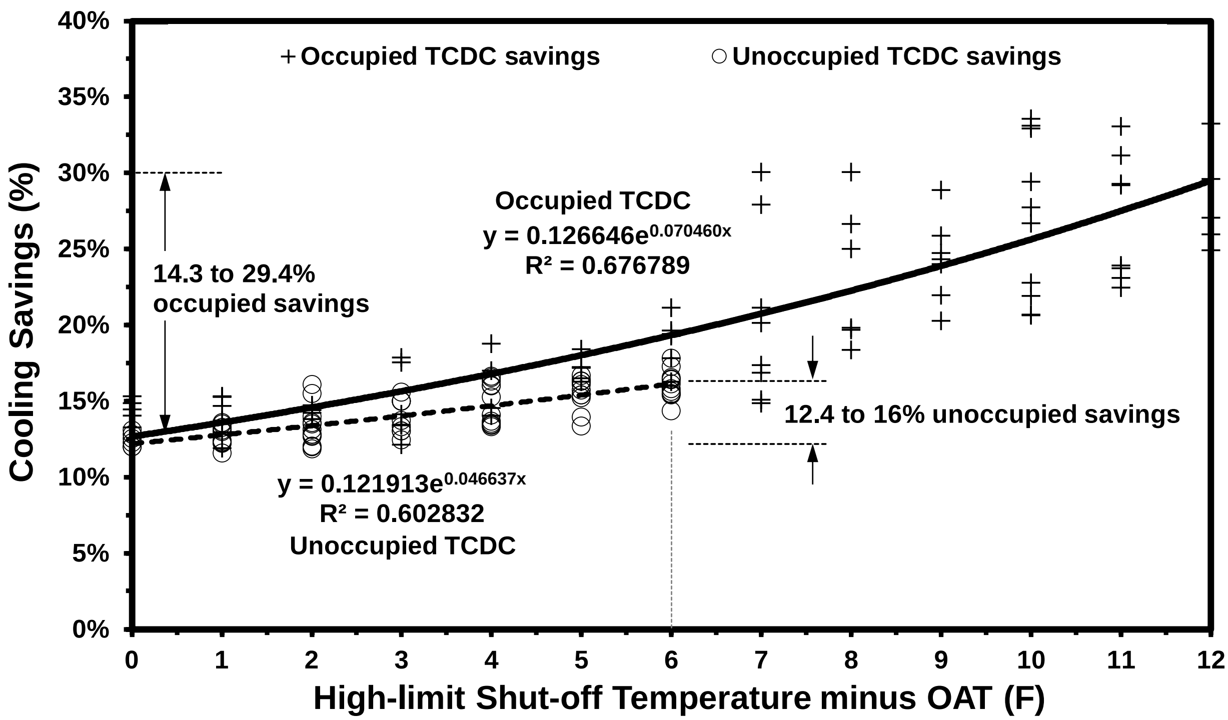

Figure 4. Economizer thermostat cooling delay correction (TCDC) savings versus HST minus OAT

Eq. 7 $y_o = 0.126646\ e^{-0.070460\ x_o}$

Where, y_o = occupied TCDC plus fan savings based on Δe_{FT} in Table 4 (dimensionless),
x_o = HST minus OAT_o which varies from 0 to 12F.

Eq. 8 $y_u = 0.121913\ e^{-0.046637 x_u}$

Where, y_u = unoccupied TCDC plus fan savings based on Δe_{FT} in Table 5 (dimensionless),
x_u = unoccupied HST minus OAT_u which varies from 0 to 6F.

Commercial thermostats do not provide a second-stage cooling (Y2) signal until a second-stage time or temperature delay is reached (3F above setpoint) (Venstar 2020). This increases cooling loads, but DOE-2.2 does not include these loads in hourly calculations (LBNL 2014). Increased loads cause AC compressors to operate longer and use 12 to 28% more energy to lower the CST by 2.2 to 4F compared to ECDC which only needs to lower CST by 2F (see Table 4 and 5). ECDC detects when outdoor conditions will not satisfy the call for cooling and

[16] Base requires fan energy plus extra DX AC energy to reduce CST by 4F versus 2F for efficient economizer.

fully opens dampers and simultaneously energizes AC compressors to save 3 to 39% more cooling energy compared to an integrated economizer with or without DCV control.

Most commercial buildings operate fans continuously which increases HVAC energy due to overventilation. Occupancy-based fan controls (OFC) switch HVAC fans from “on” to “auto” during unoccupied periods to save energy. OFC provides low-voltage signals to economizers to close dampers and reduce overventilation during unoccupied periods to save HVAC energy. OFC is modeled in DOE-2.2 by scheduling the fan off at night and setting the NIGHT-CYCLE_CTRL to “CYCLE-ON-ANY.” OFC is applicable to 13 to 30% of buildings (DNVGL 2016; Jacobs 2003).[17] The Advanced Research Project Agency-Energy (ARPA-E) SENSOR program indicates occupancy recognition technology can save 30% on HVAC energy equivalent to 2 to 4% of total US energy consumption (ARPA-E 2022).

Energy Impacts

The DOE-2.2 building energy software and the Database for Energy Efficiency Resources (DEER 2020) small retail prototypes were used to evaluate the baseline and economizer HVAC energy use and peak demand (LBNL 2014). Simulations were performed for three California climate zones: 1) coastal [CZ 6], 2) central valley [CZ 13], and 3) desert [CZ 15]. The DOE-2 software does not model cooling loads associated with thermostat or economizer second-stage time or temperature delays when the economizer cannot satisfy the thermostat call for cooling. The DOE-2.2 defaults assume perfect economizer and mechanical cooling operation, perfect outdoor airflow, no economizer dead band, and no thermostat or economizer second-stage delays. The DOE-2.2 DCV economizer model uses MIN-AIR-SCH to define outdoor airflow as a fraction of supply airflow over time.[18] Lab tests show economizers do not provide 100% outdoor airflow when fully open or 0% outdoor airflow when fully closed. The base economizer and economizer calibration plus perimeter gap sealing, OFC and HST correction measures are modeled in DOE-2.2. The base economizer and HST correction measures are modeled in DOE-2.2 using the OA-CONTROL input and OA-TEMP upper limit of 71F HST for CZ6, and 75F HST for CZ 13 and 15 (CEC 2016). An hourly post-processor is used to model cooling delay correction since these measures cannot be modeled in DOE2.2.

Cooling capacity varies by climate. Building zone 1 was modeled with 15 to 27 tons and zone 2 was modeled with 2.5 to 4.3 tons of cooling capacity. The uncalibrated base economizer with 63F HST was modeled with 17.9% OAF closed (2V), 41% OAF minimum (3-fingers open), and 65.8% OAF fully open (10V), and the base and DCV controllers with 71-75F HST were modeled with 33% OAF minimum (5.1V). Economizer calibration and perimeter gap sealing were modeled with 12% OAF closed (2V), 30% OAF minimum (5.5V), and 65.8% fully open.

Table 6 provides the DOE-2.2 base annual Energy Use Intensity (EUI) for combined cooling plus ventilation fan (kWh/ft^2 and W/ft^2) and gas heating (kBtu/ft^2) for intermittent or continuous fan operation. EUIs are provided for the base controller with 63F HST, base

[17] DNVGL 2016 (pp. 68-69) “78% of them show the fan running continuously in the as-found case, see Figure 17.” “PG&E Commercial HVAC implementer reported, finding base case fan-on only 13% of the time.” Figure 18 shows “the measure is implemented in only 2.8% of the cases where supply fan was found on. Furthermore, in 45% of cases where the fan was found in the auto or off state the implementer adjusted the fan to on, see Figure 19.” Jacobs reported 30% of HVAC systems with continuous fan operation during unoccupied periods (Jacobs 2003).

[18] “Values in MIN-AIR-SCH vary from 0.0 (no outside airflow; economizer inactive if specified) to 1 (100% outside airflow). A value of 0.001 actives the economizer” (LBNL 2014, p. 363).

controller with 71F and 75F HST, and base controller with 71F and 75F HST and Demand Control Ventilation (DCV). The average EUIs are comparable to the 2006 Commercial End Use Survey (CEUS) for retail buildings. The CEUS study provides cooling plus fan EUIs of 4.1 to 5.4 kWh/ft^2, and gas space heating of 1.1 to 6.7 kBtu/ft^2 (Itron 2006).

Table 6. DOE-2.2 base space cooling plus fan and heating annual energy use intensities (EUI)

#	Description	CZ06 kWh/ft^2	CZ06 W/ft^2	CZ06 kBtu/ft^2	CZ13 kWh/ft^2	CZ13 W/ft^2	CZ13 kBtu/ft^2	CZ15 kWh/ft^2	CZ15 W/ft^2	CZ15 kBtu/ft^2
1	63F Intermittent Fan	2.2	0.7	1.7	3.6	1.6	4.7	6.6	3.4	2.2
2	63F Continuous Fan	3.9	1.1	31.4	7.4	2.7	65.5	13.0	4.5	3.9
3	71-75F Intermittent Fan	2.2	0.8	1.7	3.5	1.5	4.6	6.3	3.0	2.2
4	71-75F Continuous Fan	3.7	1.3	13.9	7.0	2.6	34.3	12.0	4.4	3.7
5	DCV Intermittent Fan	2.6	1.0	3.1	5.7	2.2	12.6	10.3	3.9	2.6
6	DCV Continuous Fan	3.7	1.3	11.3	6.9	2.4	26.1	11.4	4.1	3.7
	Average EUI	**1.3**	**0.4**	**2.2**	**2.3**	**0.9**	**5.9**	**4.1**	**1.8**	**1.3**

Table 7 provides energy savings versus the base economizer with "default" 63F HST. Table 8 provides energy savings versus an economizer HST of 71F (CZ06) and 75F (CZ13 and CZ15). Table 9 provides energy savings versus DCV. Calibration plus perimeter gap sealing saves 2% on cooling and 14% on heating. Thermostat and economizer CDC saves 9% on cooling. HST correction saves 2% on cooling. OFC saves 10% on cooling and 4% on heating. Average savings are 21 ± 4% for cooling plus fan, 14 ± 5% for peak demand, and 18 ± 4% for heating. The payback is 2.2 years based on a cost of \$0.19/ft^2 and savings of \$0.09/ft^2-yr.[19]

Table 7. Energy savings versus base economizer with default 63F HST

Measure Description	CZ06 kWh	CZ06 kW	CZ06 Therm	CZ13 kWh	CZ13 kW	CZ13 therm	CZ15 kWh	CZ15 kW	CZ15 therm
1) Calibration + gap seal	-1.1%	2.9%	13.1%	2.7%	9.6%	13.6%	6.8%	17.1%	23.1%
2) Thermostat CDC	16.0%	7.5%		8.7%	8.6%		10.1%	11.6%	
3) Economizer CDC	2.6%	4.1%		5.4%	4.0%		6.2%	3.8%	
4) HST Correction	6.5%	0.0%		4.1%	0.0%		2.9%	0.0%	
5) OFC	20.4%	0.0%	6.2%	22.4%	0.0%	4.3%	19.9%	0.0%	6.8%
Total savings	**30.1%**	**14.5%**	**15.0%**	**27.7%**	**22.2%**	**14.9%**	**32.0%**	**32.4%**	**25.1%**

Table 8. Energy savings versus base economizer with 71F (CZ6), 75F (CZ13/15) HST

Description	CZ06 kWh	CZ06 kW	CZ06 Therm	CZ13 kWh	CZ13 kW	CZ13 therm	CZ15 kWh	CZ15 kW	CZ15 Therm
1) Calibration + gap seal	-1.0%	2.9%	12.5%	1.1%	3.5%	11.7%	2.8%	6.7%	20.0%
2) Thermostat CDC	9.8%	4.6%		2.1%	3.1%		1.6%	5.0%	
3) Economizer CDC	2.6%	4.3%		2.6%	2.5%		7.3%	4.3%	
4) HST Correction	1.4%	0.0%		-0.1%	0.0%		-0.1%	0.0%	
5) OFC	16.9%	1.0%	4.8%	17.4%	2.7%	2.9%	12.4%	3.4%	5.5%
Total savings	**17.9%**	**12.1%**	**13.9%**	**15.1%**	**9.5%**	**28.2%**	**15.4%**	**16.9%**	**21.7%**

[19] Assumes \$1500/unit, 8000 ft^2, savings of 0.51 kWh/ft^2-yr and \$0.16/kWh and 0.36 Btu/ft^2-yr and \$1/therm.

Table 9. Energy savings versus DCV with 71F (CZ6), 75F (CZ13/15) HST

Description	CZ06 kWh	CZ06 kW	CZ06 Therm	CZ13 kWh	CZ13 kW	CZ13 Therm	CZ15 kWh	CZ15 kW	CZ15 therm
1) Calibration + gap seal	-0.6%	0.3%	9.6%	1.2%	0.5%	9.3%	2.2%	0.5%	16.2%
2) Thermostat CDC	11.9%	5.5%	0.0%	2.0%			2.3%		
3) Economizer CDC	3.5%	4.5%		7.7%	5.1%		6.0%	4.5%	
4) HST Correction	1.4%			-0.1%			-0.1%		
5) OFC	-0.7%	0.0%	2.6%	17.6%	0.5%	3.4%	12.2%	0.5%	6.7%
Total savings	**16.0%**	**10.4%**	**10.4%**	**16.0%**	**5.8%**	**10.3%**	**14.0%**	**5.2%**	**18.2%**

Conclusions

Laboratory tests of four HVAC systems with economizers found an average OAF of 18.1% at closed damper positions and 41% at minimum positions. Sealing the economizer perimeter gap reduced the closed OAF to 12% and calibrating reduced the minimum OAF to 30%. The four HVAC systems are 38 to 62% less efficient than AHRI ratings due to overventilation which can significantly increase energy use in buildings with continuous fan operation. Laboratory tests of the same four HVAC units with economizer dampers fully open found an average OAF of 66% for economizer cooling which is 34% less than assumed by the HVAC industry.

Building energy simulations of prototypical retail buildings in three California climate zones indicate potential annual energy savings of 2% on cooling and 14% on heating by sealing the economizer perimeter gap and calibrating to reduce excess outdoor airflow. Optimizing cooling delay controls saves 9% on cooling. HST correction saves 2% on cooling. Reducing continuous fan operation saves 10% on cooling and 4% on heating. Potential energy savings for the proposed economizer efficiency test standard are 21% for cooling plus fan and 18% for heating which is equivalent to about 1% of total US energy consumption. These savings are comparable to other economizer efficiency studies (Taylor 2010, Wang 2011, ARPA-E 2022). The payback is 2.2 years based on a cost of $0.19/ft^2$ and savings of $0.09/ft^2$-yr.

The proposed economizer efficiency tests will be performed at three damper positions: closed, intermediate, and fully open. Indoor and outdoor test conditions for economizer-only cooling, integrated cooling (economizer plus mechanical), and mechanical-only cooling will harmonize with other standards. The proposed test procedure will indicate how cooling efficiency is impacted by economizer outdoor airflow, calibration, and controls. Including economizers in the unitary next-generation test procedure standards will improve thermal comfort, indoor air quality, and energy efficiency.

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