Smart Economizer for Commercial HVAC Systems

Robert Mowris, P.E., Verified Inc.

Peter Jacobs, P.E., Building Metrics Inc.

Abstract

Research studies indicate that 50 to 70% of air-side economizers on commercial Heating, Ventilating, and Air Conditioning (HVAC) systems are not functioning properly causing energy use to increase by 18 to 37%. Many economizers have failed sensors, failed controls or incorrect settings providing insufficient or excess outdoor airflow which reduces capacity and increases energy use. To address these issues, the California Energy Commission (CEC) 2016 building energy efficiency standards require economizer demand control ventilation, high-limit shut-off temperature controls, and fault detection diagnostics to check economizer operation and excess outdoor airflow on commercial HVAC systems with mechanical cooling capacities greater than 15.83 kW (54,000 Btu/hour). The CEC standards are based on building energy simulation models which assume perfect integration of economizer and mechanical cooling, perfect outdoor airflow, no thermostat or economizer delays or dead bands, and no unoccupied fan operation. This paper provides field and laboratory tests of a smart economizer that brings actual performance closer to the idealized performance predicted by simulation models. The smart economizer improves cooling and heating efficiency, reduces excess outdoor airflow, corrects thermostat and economizer time and temperature delays and dead bands, provides variable fan-off delays, and switches fans from “on” to “auto” during unoccupied periods. Based on laboratory and field tests, building energy simulations and analyses, average annual savings are 22.9% for cooling plus fan and 25.5% for heating. The simple payback is 1.9 years based on an installed cost of $1500/unit, and annual energy savings of $776.

Introduction

Commercial heating, ventilating, and air conditioning (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 [13]. Commercial cooling uses 32.1% of total annual US HVAC energy, heating uses 33.9%, and ventilation uses 34% due to continuous fan operation (EIA 2019). Packaged roof-top units (hereafter “units”) serve over 60% of total commercial floor area in the US (EIA 2019). Most units have an air-side “economizer” to provide a maximum outdoor airflow 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) American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1 [6].[1] Research studies show that 50 to 70% of existing commercial air-side economizers in the US are not functioning properly and improved fault detection diagnostic (FDD) controls can improve cooling efficiency by 18 to 37% or more [9, 16, 17, 21].[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 [4, 5, 28]. 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 [30].

[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 ($0.20 \times 8V + 2V$), and fully open is 10V (8V + 2V).

[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 [8] 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 (CO_2) concentrations.

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 [8]. Standards do not require FDD fan-on correction during unoccupied periods.

The CEC 2016 building standards and the 2011 PNNL study are based on the EnergyPlus building simulation program [11]. The ASHRAE 2010 study and this study are based on the DOE-2 building energy simulation program. The DOE-2 and EnergyPlus programs assume perfect integration of economizer and mechanical cooling per building standards. The model defaults assume zero outdoor airflow at the closed damper position, outdoor airflow per ASHRAE 62.1 at the minimum position, and 100% outdoor airflow when economizing. The models assume no thermostat or economizer time or temperature delays, no economizer dead band delays, and no continuous fan-on operation during unoccupied periods embodied on thermostats and economizer controllers [7, 11, 18].

This paper provides field and laboratory test results for a smart economizer or efficient economizer controller (EEC) with FDD per the 2016 California standards that brings actual performance closer to the idealized performance predicted by DOE-2.2 and EnergyPlus simulation models [23, 24, 25, 26]. The smart economizer includes: 1) continuous FDD calibration to verify the correct required outdoor airflow fraction (OAF) based on a functional relationship between the economizer actuator voltage (x) and a corresponding damper position OAF (y) (with economizer perimeter gap sealing at installation); 2) Occupancy-based fan control (OFC) switches fans from “on” to “auto” during unoccupied periods; 3) variable fan-off delay; 4) thermostat cooling delay correction (CDC) to detect when the economizer cannot satisfy the call for cooling and supersede the thermostat second-stage time and/or temperature dead band delay to fully open dampers and simultaneously energize the AC compressor(s); 5) economizer CDC to detect and override the economizer second-stage delays and energize the first-plus-second-stage AC compressors when the thermostat energizes the second-stage cooling signal; and 6) HST correction to enable economizer cooling otherwise delayed by the HST dead band unless the OAT is less than or equal to the HST minus 1.11C or 2F (or OAT ≤ HST minus 0.56C or 1F).

The smart economizer cooling and heating energy savings are based on field tests and third-party tests performed by Intertek, an ISO-certified laboratory used by manufacturers and USDOE to test HVAC equipment for compliance with Federal energy efficiency standards. Laboratory tests were performed on three new packaged HVAC units with DX Air Conditioning (AC) compressors and economizers and gas furnace or heat pump heating. The following three units were tested at Intertek: 1) 7.5-ton two-compressor packaged DX AC gas furnace unit #1, 2) 3-ton packaged DX AC gas furnace unit #4, and 3) 4-ton packaged heat pump unit #6.[4] Field tests were performed on a 10-ton two-compressor packaged DX AC gas furnace unit #8 installed on a commercial office building located in Reno, Nevada.

The unit #1, #2, #3, and #8 economizers have a default 120-minute economizer second-stage time delay [18]. Some manufacturers provide a second-stage time delay of 4 minutes [7]. Like the thermostat second-stage delays, the economizer second-stage delays limit cooling capacity to the first-stage compressor which reduces efficiency and occupant comfort. Many WIFI thermostats and BACNet systems do not provide information regarding how to optimize economizer cooling setpoints, second-stage time or temperature delays, integrated economizer plus mechanical cooling, or second-stage mechanical cooling only [31, 32, 33, 34]. These issues reduce comfort and cause inefficient economizer and cooling system operation. Table 1 provides a description of each unit. Equipment was setup in two chambers at the laboratory to emulate indoor and outdoor conditions per Air-Conditioning, Heating, and Refrigeration Institute (AHRI) 340/360 or AHRI 240/260 [1, 35]. Test

[4] One ton of cooling is defined as heat energy removed from one short ton of water (2,000 pounds or 907.1847 kg) to produce one ton of ice at 32F (0C) in 24 hours. Energy required for phase change of liquid water at 32F (0C) into solid ice at 32°F is referred to as heat of fusion equal to 144 Btu/lb times 2,000 lbs of water or 288,000 Btu of energy over 24-hour period or 12,000 Btu/hour to make one ton of ice in one day. British thermal unit (Btu) is heat required to raise temperature of one pound (0.454 kg) of water one F (0.556C). Btu is equivalent to 1055.06 joules or 251.997 calories.

conditions differ from those used to rate cooling and heating systems to match typical installations in California.[5]

Table 1: Description of laboratory and field test Units #1, #4, #6, and #8

Description	Unit #1: 7.5-ton DX AC Gas Furnace	Unit #4: 3-ton DX AC Gas Furnace	Unit #6: 4-ton Heat Pump	Unit #8: 10-ton DX AC Gas Furnace
Model	48HJF008-541	48HJM004	50HJQ005	RKMB-A120CM22E
Rated SEER/EER	11 EER	13 SEER/11.0 EER	13 SEER/10.5 EER	9 EER
Rated heat efficiency	82% Efficiency	81% Efficiency	7.8 HSPF	81% Efficiency
Rated cooling capacity, airflow, and static pressure	90,000 Btuh total, 57,182 Btuh sensible, 3000 scfm at 0.5 IWC	36,000 Btuh total and 25,009 Btuh sensible, 1050 scfm at 0.5 IWC	49,000 Btuh total and 35,600 Btuh sensible, 1600 scfm at 0.5 IWC	120,000 Btuh total and 90,000 Btuh, 4000 scfm at 0.3 IWC
Refrigerant charge	R22 105/105 oz.	R410A 102 oz	R22 192 oz	R410A 80/80 oz
Duct leakage @ 25 Pa	6%	6%	6%	5%
Rated heating capacity, airflow, static pressure	72,900/102,500 Btu/hr 3000 scfm at 0.5 IWC	40,087/49,985 Btu/hr, 1,050 scfm @ 0.4 IWC	46,500 Btu/hr 1,600 scfm at 0.5 IWC	112,000/225,000 Btuh 4,000 scfm at 0.8 IWC
Fan-off delay	0 seconds heating	Fixed 30 sec. heating	0 seconds heating	Fixed 90 sec. heating

Test Equipment Laboratory Setup

Laboratory tests were performed at Intertek, an AHRI-certified laboratory, located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI equipment efficiency testing for the U.S. Department of Energy (DOE) compliance and enforcement program to meet energy conservation standards required by the Energy Policy and Conservation Act of 1975 as amended [15]. The test facility consists of climate-controlled indoor and outdoor chambers where ducts, evaporator, condenser, furnace, or hydronic heating equipment and forced air units are located. HVAC systems and test equipment were assembled and installed in the test chambers by laboratory technicians. Cooling verification tests were performed according to the AHRI Standard 340/360 2019 [1]. Economizer airflow tests were performed according to ANSI/ASHRAE 41.2-1987 Standard Methods for Laboratory Airflow Measurement [2]. Thermal efficiency tests were performed according to ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006 [3]. Laboratory test equipment was calibrated per ISO 17025 by an accredited provider per the International Laboratory Accreditation Cooperation (ILAC) [19].

Laboratory Tests

Laboratory and field tests were performed under steady-state conditions to measure base and smart economizer cooling capacity, efficiency, and OAF for a range of economizer actuator control voltages and damper positions [27]. Figure 1 shows laboratory tests of damper position OAF (y) versus economizer actuator control voltage (x) for unit #4 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 closed position provides 0% and fully open provides 100% OAF. Sealing the outdoor air damper perimeter gap reduces outdoor airflow by 9.5% from 23.5% to 14% at the 2V closed damper position. 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%. Not sealing the return air perimeter gap reduces outdoor airflow by 0.5% from 66.3 % to 65.5% at the 10V fully open position. However, sealing both the return and supply air damper perimeter gaps increases outdoor airflow and economizer cooling capacity by 8% or more at the 10V fully open position (not shown).

[5] Cooling tests were performed at 95F (35C) dry bulb (DB) OAT, and IAT DB 80F (26.67C), WB 67F (19.44C), OAT and 75F (23.9C) DB indoor air temperature (IAT) and 62F wet bulb (16.67C) (WB). Gas heating tests were performed at 47F (8.33C) DB OAT and 72F (22.2C) DB IAT and 53F (17.22C) WB (AHRI 2019).

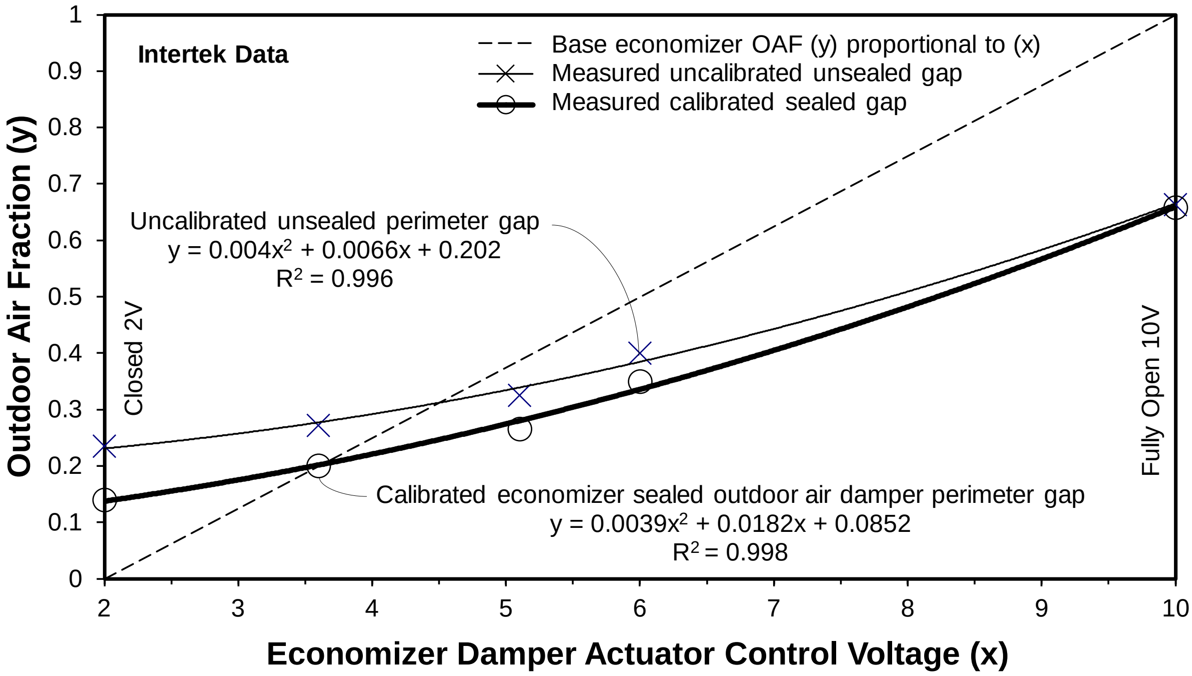

Figure 1. Laboratory tests Unit #4 base and calibrated economizer with sealed perimeter gap

Sealing the economizer perimeter gap between the economizer frame and the HVAC system cabinet reduces uncontrolled outdoor airflow. The sealing method is performed using tape, mastic, or other sealants [24]. The economizer calibration method determines a functional relationship between the actuator voltage (x) and a corresponding damper position OAF (y) [23]. The calibration method measures a set of x-versus-y data for at least two damper positions including: a closed damper position, at least one intermediate damper position, and a fully open damper position. The coefficients of the functional relationship are calculated using the x-versus-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 [6]. The following equations shown in Figure 1 provide the relationship between the economizer actuator voltage (x) and the corresponding OAF (y) for the unsealed and sealed economizer perimeter gap.

Eq. 1 $y_{base} = 0.004\, x_i^2 + 0.0066\, x_i + 0.202$

Where, y_{base} = base OAF (dimensionless), and

x_i = base economizer actuator voltage from 2V to 10V (Volts).

Eq. 2 $y_c = 0.0039\, x_i^2 + 0.0182\, x_i + 0.0852$

Where, y_c = calibrated OAF with sealed perimeter gap (dimensionless), and

x_i = calibrated economizer actuator voltage from 2V to 10V (Volts).

Figure 2 shows the weighted average savings versus part load ratio (PLR) based on Intertek tests for the smart economizer variable fan-off delay for cooling (unit #6) and heating (unit #4). The PLR is the ratio of delivered cooling or heating capacity divided by the rated capacity for a given hour. Weighted average savings are based on fixed fan-off delays of 45, 60, and 90 seconds for the base case.

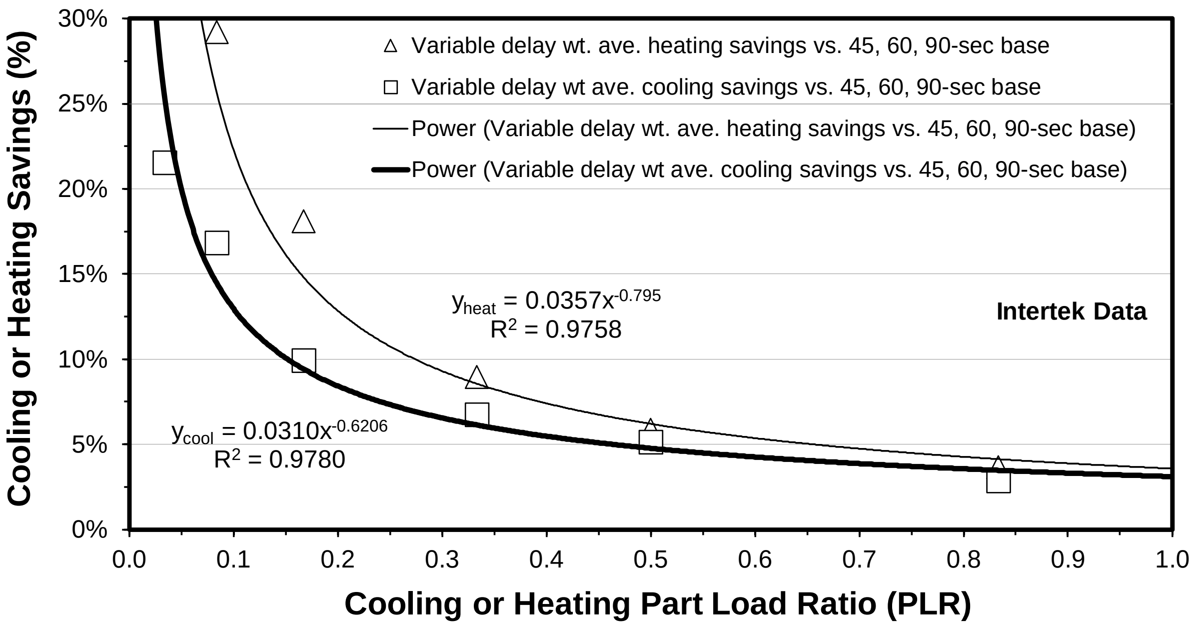

Figure 2. Laboratory tests Unit #6 (cooling) and Unit #4 (heating) variable fan-off delay vs. base

The cooling and heating variable fan-off delay measures are modeled in DOE-2.2 using an hourly post processor and the following equations. Savings occur when building is unoccupied and the fan is operating intermittently with thermostat calls for cooling or heating.

Eq. 3 $y_{cool} = 0.031\ x^{(-0.6206)}$

Where, y = cooling energy savings (dimensionless), and

x = PLR hourly cooling capacity divided by total cooling capacity (dimensionless).

Eq. 4 $y_{heat} = 0.0357\ x^{(-0.795)}$

Where, y = gas heating energy savings (dimensionless), and

x = PLR hourly heating capacity divided by total heating capacity (dimensionless).

Table 2 provides Intertek laboratory tests of unit #1 with and without economizer or compressors when occupied. The rated efficiency for this unit is 11.0 and the rated sensible EER is 7.7 EER. Fig. 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. Table 2 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 (12.78C) (27.3%) and 60F (15.56C) OAT (11.5%). At 65F (18.33C) 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 (15.56C) or greater OAT. The economizer cooling delay correction (ECDC) provides annual cooling savings of 4.9 ± 1.1% by superseding the thermostat and or economizer second-stage delays and energizing the first-plus-second-stage AC compressors when the thermostat energizes the second-stage cooling signal. The ECDC method is more efficient than the first-stage AC compressor for all OAT conditions when internal loads are equivalent to cooling loads.[6] Fan power and airflow are similar for each test, but cooling capacity and total power are greater. The AC compressor satisfies the thermostat sooner with 4.9% less annual compressor operating hours and energy use.

[6] Intertek maintained 75F (23.89C) DB and 62F (16.67C) WB indoor conditions to emulate an occupied commercial building.

Table 2. Lab 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 3 shows the ECDC cooling savings for OAT conditions ranging from 63F to 100F for unit #1 based on data provided in Table 2. Figure 3 shows economizer cooling is only more efficient than ECDC when the OAT is less than 61F which is the default (HST minus dead band) 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 [7] to 120 minutes [18]. The ECDC measure is modeled with the DOE-2.2 hourly post processer and the following equation when OAT is greater than 63F (17.22C).

Eq. 5 $y = 0.844407 \, \mathrm{LN}(x) - 3.417134$

Where, y = ECDC energy savings (dimensionless), and

x = OAT (F) based on the DOE-2.2 hourly data.

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).

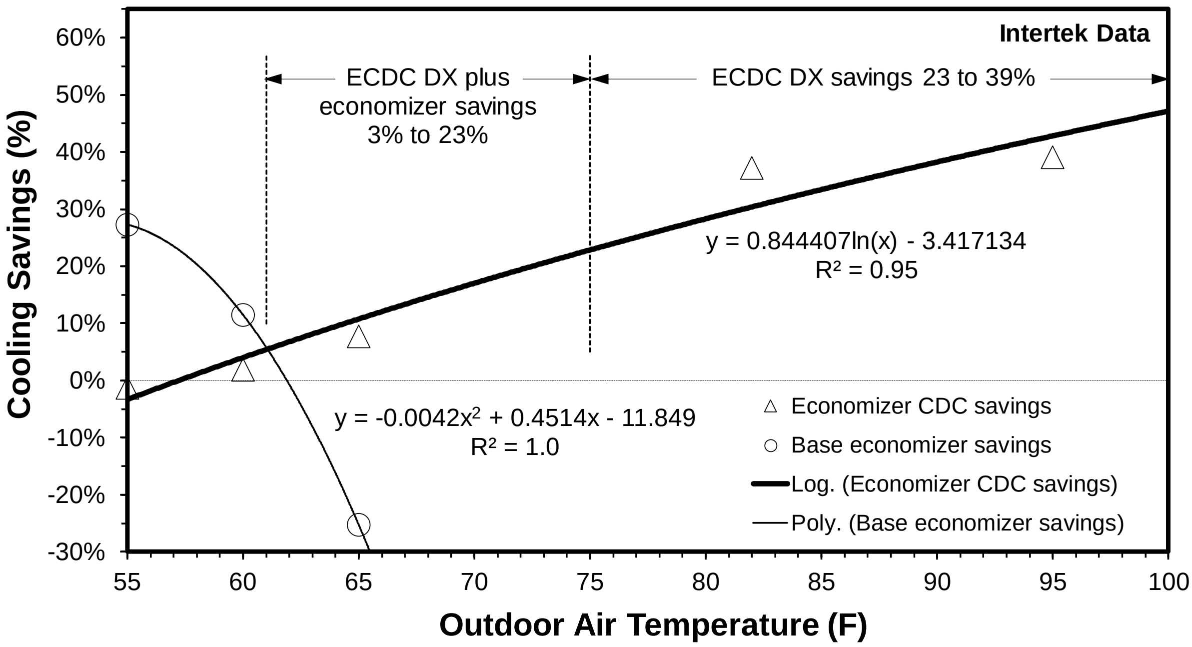

Figure 3. Lab tests of economizer cooling delay correction savings vs. OAT when occupied

Field Tests of the Smart Economizer

Figure 4 provides field tests of the 10-ton unit #8 with base economizer and 63F default HST and the thermostat cooling delay correction (TCDC) and variable fan-off delay methods [25, 26]. Figure 4 shows the TCDC method improves cooling efficiency for these tests by 32.9% compared to the base economizer with 63F HST. Average annual cooling savings for the TCDC are 7.2% $\pm$ 2.9% based on DOE-2 simulations discussed below. The TCDC fully opens the economizer damper and simultaneously energizes the AC compressor to minimize compressor operation and maximize efficiency and thermal comfort.[7] For this example, the TCDC improves cooling efficiency by 27% compared to the base economizer which closes the damper when the OAT is greater than the default 63F (17.22C) HST [18]. The variable fan off delay improves cooling efficiency by about 12% (net 6.2%) compared to the base 90-second fan-off delay which only increases efficiency by 5.8%.[8] With 75F (23.89C) HST [8] instead of 63F (17.22C) 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 4).

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

[8] FDD fan-off method monitors and controls the fan G signal and provides a variable fan-off delay which may be embodied in a thermostat per US 10,281,938 and US 11187425. Base HVAC systems do not provide a variable fan-off delay.

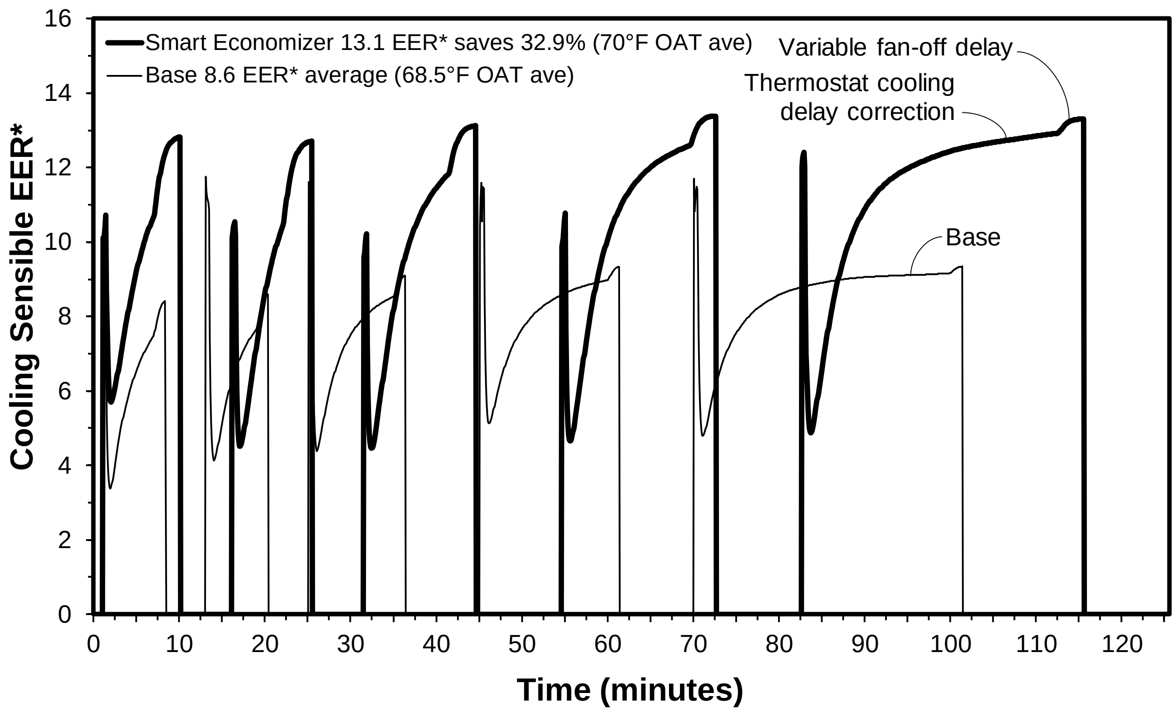

Figure 4. Field tests #8 variable fan-off delay and thermostat cooling delay correction vs. base

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 [7, 18, 29]. These delays require about 12.4 to 29.4% more compressor operation (see Table 3 and 4). TCDC savings are calculated using the following 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. 6 $Q_{net} = Q_{sc} + (Q_e + Q_i)$

Where, Q_{net} = net DX AC sensible heat removal rate (Btu) [Table 3 or 4 column g],

Q_{sc} = average DOE-2 DX coil sensible cooling (Btu) [Table 3 or 4 column e],

Q_e = average DOE-2 economizer heat removal (Btu) [Table 3 or 4 column b],

Q_i = average DOE-2 sensible heat added to room air (Btu) [Table 3 or Table 4 column c].

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

Eq. 7 $e_c = e_{ac}\ (1\text{-}Q_v/Q_{sc})$

Where, e_c = corrected DOE-2 AC power (kWh) [Table 3 or 4 column i],

e_{ac} = average DOE-2 hourly DX AC plus fan power (kWh) [Table 3 or 4 column h],

Q_v = heat added to room air causing 2F CST increase (Btu) [Table 3 or 4 column d].[9]

Eq. 8 $\Delta e_{FT} = 1\text{-}e_{ac}/e_c)$

Where Δe_{FT} = TCDC savings when occupied or unoccupied [**Table 3** or **4** column j].

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

Table 3 provides TCDC savings using these two equations based on occupied DOE-2.2 hourly data. Table 4 provides the calculations based on unoccupied DOE-2.2 hourly data.

Table 3. 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%

Figure 5 provides regression Equation 9 used to calculate TCDC savings when the building is occupied. Figure 5 also provides regression Equation 10 used to calculate the TCDC 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.[10] The TCDC occupied savings are 14.3 to 29.4% (upper curve), and unoccupied savings are 12.4 to 16% (lower curve) depending on the HST minus OAT.

Table 4. Thermostat cooling delay correction savings based on unoccupied DOE-2.2 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%

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

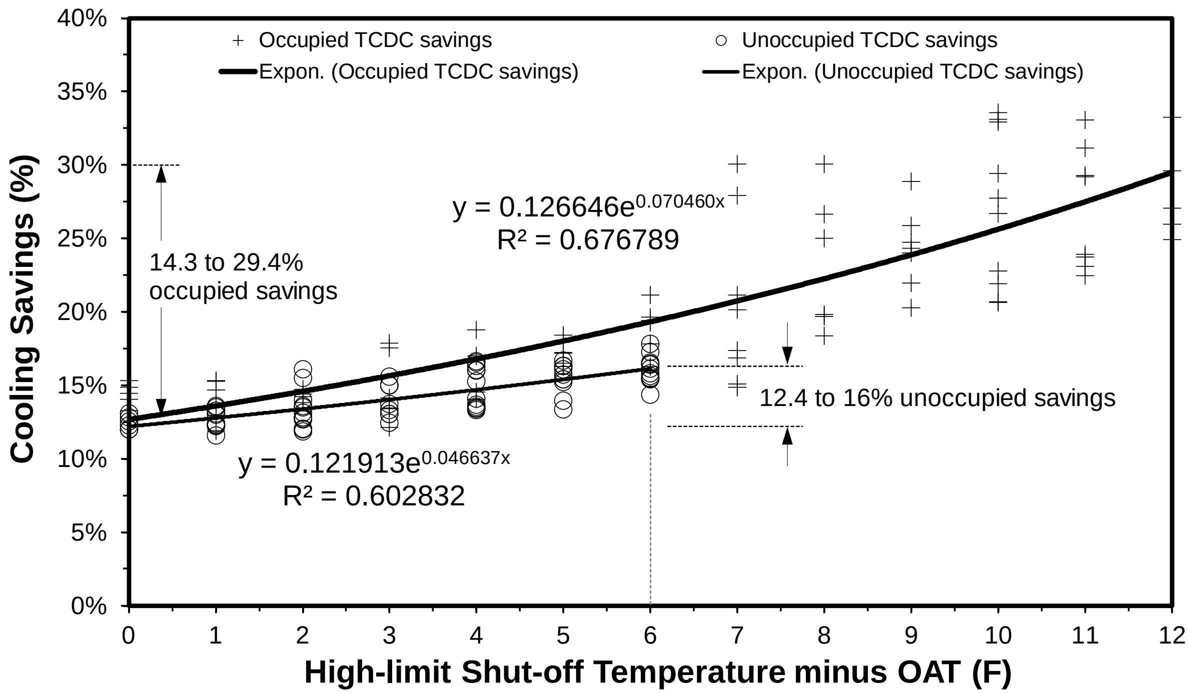

Figure 5. Thermostat cooling delay correction (TCDC) savings versus HST minus OAT

Eq. 9 $y_o = 0.126646\ e^{-0.070460\ x_o}$

Where, y_o = occupied TCDC plus fan savings based on Δe_{FT} in Table 3 (dimensionless),

x_o = HST minus OAT_o which varies from 0 to 12F.

Eq. 10 $y_u = 0.121913\ e^{-0.046637 x_u}$

Where, y_u = unoccupied TCDC plus fan savings based on Δe_{FT} in Table 4 (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 (typically 3F above the setpoint) (Venstar 2020). This increases the cooling load, and the DOE-2.2 program does not include this load in the hourly calculations (LBNL 2014). In actual buildings, this increased load causes the AC compressor to operate longer and use about 12 to 28% more energy to lower the CST by 2.2 to 4F compared to the smart economizer cooling delay correction method which only needs to lower CST by 2F (see Table 3 and Table 4). The smart economizer fully opens dampers and simultaneously energizes AC compressors when the method detects outdoor conditions are unable to satisfy the call for cooling which saves 3 to 39% more cooling energy compared to an integrated economizer with or without DCV control.

Occupancy-based Fan Control (OFC) detects, reports, and switches fans from “on” to “auto” during unoccupied periods. OFC is modeled in DOE-2.2 by scheduling the fan off at night and setting the NIGHT-CYCLE_CTRL to “CYCLE-ON-ANY.” In practice, the smart economizer, a smart thermostat, or dedicated OFC will perform the method. OFC is applicable to 13 to 30% of buildings [12, 21]. [11] The variable fan-on delay is applicable to 87% of buildings with intermittent fan operation (i.e., 1-13%).

[11] DNVGL 2016 [12] (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 having continuous fan operation during unoccupied periods [21].

Energy Impacts

The DOE-2.2 building energy software and the Database for Energy Efficiency Resources [10] small retail building prototypes were used to evaluate the baseline and smart economizer HVAC energy use and peak demand [22]. 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.[12] Economizers do not provide 100% outdoor airflow when fully open or 0% outdoor airflow when fully closed. The base economizer and the smart economizer calibration plus gap sealing, occupancy-based fan control, 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 per the 2016 CEC standards (p. 209, Table 140.4E, 71F HST for CZ6, and 75F HST for CZ 13 and 15). An hourly post processor is used to model the thermostat and economizer cooling delay correction and variable fan-off delay since these measures cannot be modeled in DOE2.2.

Table 5 provides a summary of the modeling assumptions for the retail sales floor area (zone 1) and the non-sales floor area (zone 2 including the office, restrooms, break room, and storage area). The zonal cooling capacity varies by climate. 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 (6.4V), 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).[13] The smart economizer with calibration and perimeter gap sealing was modeled with 12% OAF closed (2V), 30% OAF minimum (5.5V), and 65.8% fully open (10V).

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 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 [20].

[12] "Values in MIN-AIR-SCH vary from 0.0 (no outside air flow; economizer inactive if specified) to 1 (100% outside airflow). A value of 0.001 actives the economizer" (LBNL 2014, p. 363).
[13] Average OAF values for the base and smart economizer are based on laboratory tests of units #1 and #4.

Table 5. Retail building modeling assumptions

Description	CZ06	CZ13	CZ15
Cool capacity sales zone 1 ft^2/ton	425.6	297.7	233.4
Cool capacity non-sales area zone 2 ft^2/ton	642.8	476.6	368.4
Heat capacity retail zone 1 Btuh/ft^2	36	55.5	62.4
Heat capacity retail zone 2 Btuh/ft^2	22.7	32.7	37.3
Lighting power (LPD) zone 1 W/ft^2 (zone 2 is 0.77 W/ft^2)	1.5	1.5	1.5
Equipment power (EPD) zone 1 W/ft^2 (zone 2 is 1.0 W/ft^2)	1.0	1.0	1.0
Floor area per person maximum zone 1 (zone 2 is 450 ft^2/person)	45	45	45
U-value roof Btu/F-ft^2 (U-value walls 0.29 Btu/F-ft^2)	0.08	0.06	0.06
Zone 1 window SHGC (window/wall ratio 0.25, zone 2 none)	0.39	0.36	0.36
Window U–value Btu/F-ft^2	0.77	0.47	0.47
Sales floor area zone 1 ft^2 (Non-sales zone 2 floor area 1,600 ft^2)	6,400	6,400	6,400
Cooling Equipment Elect. Input Ratio (EIR)	0.2552	0.2552	0.2552
Heating Equipment Input Ratio (HIR)	1.282	1.282	1.282
HVAC equipment airflow cfm/ton	376	376	376

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	0.5	1.7	3.6	1.1	4.7	6.6	2.6	0.3
2	63F Continuous Fan	3.9	0.7	31.4	7.4	2.0	65.5	13.0	3.4	34.8
3	71-75F Intermittent Fan	2.2	0.4	1.7	3.5	1.0	4.6	6.3	2.3	0.3
4	71-75F Continuous Fan	3.7	0.7	13.9	7.0	1.8	34.3	12.0	3.3	14.1
5	DCV Intermittent Fan	2.6	0.5	3.1	5.7	1.5	12.6	10.3	3.0	1.7
6	DCV Continuous Fan	3.7	0.7	11.3	6.9	1.6	26.1	11.4	3.1	10.8
	Average EUI	**1.3**	**0.3**	**2.2**	**2.3**	**0.6**	**5.9**	**4.1**	**1.3**	**1.6**

Table 7 provides smart economizer savings versus the base economizer with “default” 63F (17.22C) high-limit EST. Table 8 provides smart economizer savings versus the base economizer with a HST of 71F (CZ06) and 75F (CZ13 and CZ15). Table 9 provides smart economizer savings versus the DCV economizer with a 71F HST (CZ06) and 75F HST (CZ13 and CZ15). Depending on climate zone, the annual smart economizer cooling savings are 15 to 37% or 0.2 to 1.51 kWh/ft^2-yr compared to the base economizer control strategies. Annual heating savings are 15 to 38% or 0.34 to 2.25 kBtu/ft^2-yr. The average smart economizer cooling plus fan savings are 22.9 $\pm$ 4.8%, peak savings are 15.1 $\pm$ 5.1%, and annual heating savings are 25.5 $\pm$ 4.2%. HVAC savings are comparable to savings identified in other economizer studies [28, 30].

Table 7. Energy savings for smart economizer vs. 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) OFC “on” to “auto”	20.4%	0.0%	6.2%	22.4%	0.0%	4.3%	19.9%	0.0%	6.8%
3) Variable fan-off delay	5.5%	1.8%	14.1%	6.0%	2.0%	16.9%	6.5%	2.1%	18.8%
4) Thermostat CDC	16.0%	7.5%		8.7%	8.6%		10.1%	11.6%	
5) Economizer CDC	2.6%	4.1%		5.4%	4.0%		6.2%	3.8%	
6) HST Correction	6.5%	0.0%		4.1%	0.0%		2.9%	0.0%	
Total savings	**34.0%**	**15.7%**	**24.8%**	**31.9%**	**23.6%**	**26.7%**	**36.6%**	**33.9%**	**38.3%**

Table 8. Energy savings for smart economizer vs. base 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) OFC “on” to “auto”	16.9%	1.0%	4.8%	17.4%	2.7%	2.9%	12.4%	3.4%	5.5%
3) Variable fan-off delay	5.0%	1.7%	14.1%	6.0%		16.9%	6.5%	2.1%	18.8%
4) Thermostat CDC	9.8%	4.6%		2.1%	3.1%		1.6%	5.0%	
5) Economizer CDC	2.6%	4.3%		2.6%	2.5%		7.3%	4.3%	
6) HST Correction	1.4%	0.0%		-0.1%	0.0%		-0.1%	0.0%	
Total savings	**21.4%**	**13.2%**	**23.8%**	**15.1%**	**9.5%**	**28.2%**	**19.9%**	**18.4%**	**34.8%**

Table 9. Energy savings for smart economizer vs. DCV with 71F (CZ6), 75F (CZ13/15) HST

Description	CZ06 kWh	CZ06 kW	CZ06 Heat	CZ13 kWh	CZ13 kW	CZ13 Heat	CZ15 kWh	CZ15 kW	CZ15 Heat
1) Calibration + gap seal	-0.6%	0.3%	9.6%	1.2%	0.5%	9.3%	2.2%	0.5%	16.2%
2) OFC “on” to “auto”	-0.7%	0.0%	2.6%	17.6%	0.5%	3.4%	12.2%	0.5%	6.7%
3) Variable fan-off delay	0.0%	0.0%	7.4%	0.6%		8.1%	1.2%		4.4%
4) Thermostat CDC	11.9%	5.5%	0.0%	2.0%			2.3%		
5) Economizer CDC	3.5%	4.5%		7.7%	5.1%		6.0%	4.5%	
6) HST Correction	1.4%			-0.1%			-0.1%		
Total savings	**16.0%**	**10.4%**	**15.6%**	**16.4%**	**5.8%**	**16.0%**	**14.9%**	**5.2%**	**21.3%**

Discussion

Research studies indicate commercial air-side economizers can provide 15 to 37% cooling and heating savings with improved FDD controls to check proper operation and excess outdoor airflow, DCV, multi-speed fans, and 69 to 75F HST control settings. To capture these savings, the CEC building standards require economizer DCV, 69 to 75F HST control settings, and FDD to check economizer operation and excess outdoor airflow [8]. However, no standards exist to calibrate and optimize economizer performance or detect and correct continuous fan-on faults during unoccupied periods. Smart thermostats and BACNet systems do not provide information regarding how to optimize economizer cooling setpoints, second-stage time or temperature delays, integrated economizer plus mechanical cooling, or second-stage mechanical cooling only [31, 32, 33, 34]. These issues reduce comfort and cause inefficient economizer and cooling system operation. The CEC standards are based on building simulation models which assume perfect integration of economizer and mechanical cooling operation, perfect outdoor airflow, no delays or dead bands, and no unoccupied fan operation. The smart economizer provides measures to overcome these issues. Economizer calibration with perimeter gap sealing saves 1.6 ± 1.4% on cooling, 4.9 ± 3% on peak kW, and 14.3 ± 2.5% on heating. Occupancy-based fan control saves 15.4 ± 3.8% on cooling plus fan and 4.8 ± 0.9% on heating. Variable fan-off delays save 4.1 ± 1.5% on cooling and 13.3 ± 2.9% on heating. Thermostat and economizer cooling delay correction detects when economizer cooling cannot satisfy the call for cooling and provides economizer plus DX cooling or second-stage DX cooling to improve comfort and save 7.2 ± 2.9%. HST correction saves 1.8 +/- 1.3% by enabling economizer cooling otherwise delayed. Average cooling plus fan savings are 22.9% ± 4.8%, peak demand savings are 15.1 ± 5.1%, and heating savings are 25.5 ± 4.2%. The simple payback is 1.9 years based on $1500/unit and annual savings of $776.[14] California uses 0.74 quadrillion Btu (quads) or 0.79 exajoules (EJ) per year for commercial cooling and heating (EIA 2019). The potential annual energy savings for the smart economizer are 0.08 quadrillion Btu (quads) or 0.084 exajoules (EJ) or 1% of California’s total annual energy use of 8 quads or 8.4 EJ in 2018.[15]

[14] Simple payback assumes 8,000 ft^2 building and electricity savings of 22.9% or 0.57 kWh/ft^2-yr and $0.16/kWh (eia.gov/electricity/). Natural gas savings of 25.5% or 0.52 Btu/ft^2-yr and $1/therm (eia.gov/dnav/ng/hist/n3020ca3m.htm).
[15] California State Energy Profile. 2018 total 7.967 quads. https://www.eia.gov/state/print.php?sid=CA. Commercial weighting 32.1% cooling, 33.9% heating, and 34% ventilation (EIA 2019 [13], Table E1, E5, and CE3.1).

Conclusions

Research studies indicate that 50 to 70% of economizers on commercial HVAC systems are not functioning properly and improved FDD controls to check proper operation and excess outdoor airflow, DCV, multi-speed fans, and 69 to 75F HST control settings can provide 15 to 37% cooling and heating savings. To capture these savings, the CEC building energy efficiency standards require DCV, 69 to 75F HST control settings, and FDD to check economizer operation and excess outdoor airflow. However, no standards exist to calibrate and optimize economizer performance or detect and correct continuous fan-on faults during unoccupied periods. The CEC standards and supporting research studies are based on building simulation models which assume perfect integration of economizer plus DX cooling operation, perfect outdoor airflow, no delays, no dead bands, and no unoccupied fan operation. The smart economizer reduces excess outdoor airflow, corrects time and temperature delays, eliminates, or mitigates dead bands, provides variable fan-off delays, and occupancy-based fan control to bring actual system performance closer to idealized performance predicted by simulation models. Laboratory and field tests of the smart economizer installed on packaged HVAC systems demonstrate cost-effective energy savings. Building energy simulations of prototypical retail buildings in three California climate zones indicate that the smart economizer provides annual cooling plus fan savings of 22.9 $\pm$ 4.8%, peak savings of 15.1 $\pm$ 5.1%, and annual heating savings of 25.5 $\pm$ 4.2%. The simple payback is 1.93 years based on $1500/unit and annual energy savings of $776.

References

[1] AHRI 2019. 340/360 Standard for Performance Rating of Commercial and Industrial Unitary Air-conditioning and Heat Pump Equipment. Arlington, VA: AHRI.

[2] ANSI/ASHRAE 1987. ASHRAE 41.2-1987 Standard Methods for Laboratory Airflow Measurement. New York, NY: ANSI.

[3] ANSI/CSA (ANSI/Canadian Standards Association). 2006. ANSI Z21.47-5th Edition 2006/CSA 2.3-5th Edition 2006– Standard for Gas-Fired Central Furnaces. New York. NY: ANSI.

[4] ANSI/ASHRAE 2013. Standard 90.1-2013 -- Energy Standard for Buildings Except Low-Rise Residential Buildings. New York, NY: ANSI.

[5] ANSI/ASHRAE/ICC/USGBC/IES 2017. Standard 189.1-2017 – Standard for the Design of High-Performance Green Buildings. New York, NY: ANSI.

[6] ANSI/ASHRAE/IES 2019. ASHRAE 62.1-2019. Standard 62.1. Standard Ventilation for Acceptable Indoor Air Quality. New York, NY: ANSI.

[7] BELIMO. 2013. Belimo ZIP Economizer™ Installation and Operation Manual, Danbury, CT 06810: Belimo. https://www.belimo.us/shop/en_US/Retrofit/Economizer/c/17708-17672

[8] CEC 2015. 2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. CEC-400-2015-037-CMF, Sacramento, CA: CEC.

[9] Cowan, A. 2004. Review of Recent Commercial Roof Top Unit Field Studies in the Pacific Northwest and California. White Salmon, WA: New Buildings Institute. https://newbuildings.org/sites/default/files/NWPCC_SmallHVAC_Report_R3_.pdf

[10] CPUC (California Public Utilities Commission). 2020. DEER (Database for Energy Efficiency Resources). San Francisco, CA: CPUC. http://www.deeresources.com/

[11] Crawley, D., L. Lawrie, C. Pedersen, F. Winkelmann 2000. EnergyPlus: Energy Simulation Program. ASHRAE Journal 42(4):49-56. Atlanta, GA.

https://www.researchgate.net/publication/230606369_EnergyPlus_Energy_Simulation_Program

[12] DNVGL 2016. Impact Evaluation of 2013-14 HVAC3 Commercial Quality Maintenance Programs. San Francisco, CA: CPUC. http://www.calmac.org/publications/HVAC3ImpactReport_0401.pdf

[13] EIA 2019. Commercial Buildings Energy Consumption Survey (CBECS). Washington, DC: EIA. https://www.eia.gov/consumption/

[14] EIA 2020. California State Energy Profile. Washington, DC: EIA. https://www.eia.gov/state/print.php?sid=CA

[15] GAO (Government Accountability Office) 1975. S. 622 — 94th Congress: Energy Policy and Conservation Act. Public Law 94–163, 89 Stat. 871. Washington DC: GAO https://www.govtrack.us/congress/bills/94/s622

[16] Hart, R., D. Morehouse, W. Price. 2006. The Premium Economizer: An Idea Whose Time Has Come. In Proceedings of the 2006 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE.

[17] Heinemeier, K. 2018. Free Cooling: At What Cost? In Proceedings of the 2018 ACEEE Summer Study on Energy Efficiency in Buildings. Washington, DC: ACEEE.

[18] Honeywell 2018. JADE Economizer Module (JADE W7220), Golden Valley, MN: Honeywell. https://customer.honeywell.com/resources/techlit/TechLitDocuments/62-0000s/62-0331.pdf

[19] ISO (International Standards Organization). 2017. ISO/IEC 17025 General Requirements for the Competence of Testing and Calibration Laboratories. Geneva, Switzerland: ISO.

[20] Itron Inc. 2006. Commercial End Use Survey. Published by the California Energy Commission (CEC). CEC-400-2006-005. Sacramento, CA.

[21] Jacobs, P., and C. Higgins. 2003. Small HVAC System Design Guide. P500-03-082-A12. Sacramento, CA: CEC. https://newbuildings.org/sites/default/files/A-12_Sm_HVAC_Guide_4.7.5.pdf

[22] LBNL (Lawrence Berkeley National Laboratory) and Hirsch, J. 2014. DOE-2.2 Building Energy Use and Cost Analysis Program Volume 2: Dictionary. Berkeley, CA: LBNL. http://doe2.com/download/doe-22/DOE22Vol2-Dictionary_48r.pdf

[23] Mowris, R., 2018, Apparatus and Methods to Measure Economizer Outdoor Air Fractions and Fault Detection Diagnostics of Airflow, Cooling Capacity, and Heating Capacity. US 10,001,289. 18 June 2018. Washington, DC: USPTO. Mowris, R., J. Walsh. 2021. Economizer Controller Calibration. US 11,029,057, 8 June 2021. Washington DC: USPTO.

[24] Mowris, R., J. Walsh. 2019. Fan Controller. US 9,671,125. 6 June 2019. Washington, DC: USPTO. Mowris, R., J. Walsh. 2021. Economizer Perimeter Gap Sealing. US 11,029,061. 8 June 2021. Washington DC: USPTO. Mowris, R., J. Walsh. 2021. Fan-on Detection and Correction. US 11,175,060. 16 Nov. 2021. Washington, DC: USPTO.

[25] Mowris, R., 2020. Apparatus and Methods to Determine Economizer Faults. US 10,663,186. 26 May 2020. Washington, DC: USPTO. Mowris, R., J. Walsh. 2021. Economizer Cooling Delay Correction. US 11022335. 1 June 2021. Washington DC: USPTO.

[26] Mowris, R., J. Walsh. 2020a. Fault Detection Diagnostic Variable Differential Variable Delay Thermostat. US 10,712,036. 17 July 2020. Washington, DC: USPTO. Mowris, R., J. Walsh. 2021. Thermostat Variable Fan-off Delay. US 11,187,425. 30 Nov 2021. Washington, DC: USPTO.

[27] R. Mowris, E. Jones, R. Eshom, K. Carlson, J. Hill, P. Jacobs, J. Stoops. 2015. Laboratory Test Results of Commercial Packaged HVAC Maintenance Faults. Prepared for the California Public Utilities Commission. Prepared by Robert Mowris & Associates, Inc. (RMA). http://www.calmac.org/publications/RMA_Laboratory_Test_Report_2012-15_v3.pdf

[28] Taylor, S., C. Cheng. 2010. Economizer High Limit Controls and Why Enthalpy Economizers Don't Work. 2010. ASHRAE Journal. 52. 12-28. Atlanta, GA: ASHRAE.

[29] Venstar 2020. Venstar Commercial Thermostat T4900 Manual, Venstar Inc., Chatsworth, California: https://files.venstar.com/thermostats/voyager/documents/T4900_manual_v2.pdf

[30] Wang. W., Y. Huang, S. Katipamula, M. Brambley. 2011. Energy Savings and Economics of Advanced Control Strategies for Packaged Air-Conditioning Units with Gas Heat, PNNL-20955. Richland, WA: Pacific Northwest National Laboratories. https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20955.pdf

[31] Carrier. 2020. ComfortVu Building Automation System Network (BACNet) Thermostat Plus Model TBPL-H Installation and Operation Guide. Palm Beach, FL: Carrier Corporation. https://www.shareddocs.com/hvac/docs/1000/Public/0C/11-808-706-01.pdf

[32] Honeywell. 2021. TC500A Commercial Thermostat Connected Device for Commercial Buildings. Golden Valley, MN: Honeywell. file:///C:/D-Drive/Honeywell/Thermostats/HBT-BMS-31-00400M-TC500A-Commercial-Thermostat-Userguide.pdf

[33] Ecobee. 2021. EMS System Set-up. Toronto, CA: Ecobee Inc. https://support.ecobee.com/s/articles/EMS-System-Set-up

[34] Google. 2021. Learn about multistage heating and cooling system: This article applies to the Google Nest Learning Thermostat (3rd gen) only. Mountain View, CA: Google Inc. https://support.google.com/googlenest/answer/9235693?hl=en

[35] AHRI 2017. 210/240 2017 Standard for Performance Rating of Unitary Air-conditioning & Air-source Heat Pump Equipment. Arlington, VA: AHRI.