Final Project Report: RTU/Economizer Analysis and Field Assessment

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EXECUTIVE SUMMARY

Space conditioning and ventilation consume a significant portion of the energy used in existing California office buildings.[1] While past building code measures achieved energy savings, California needs deeper mechanical heating, ventilation, and air conditioning (HVAC) systems savings to meet its 2030 nonresidential Zero Net Energy goal. To encourage the adoption of higher efficiency HVAC equipment and practices, the performance and cost baselines to which they are compared must be representative of real-world performance and costs. For many building types, rooftop units (RTUs) are the baseline system. RTUs are a type of HVAC system, contained in a single unit, that modulate outdoor air and come equipped with airside economizers which provide ventilation required by building codes. Additionally, economizers produce cooling mode energy savings of 10-60% depending on climate zone and building type. RTU are most often dual fuel units with gas heating and electric vapor compression cooling, but they are also available is electric only heat pump units.

Historically, installation, commissioning, and maintenance of RTU/economizer systems often ignored the potential to maximize efficiency. Code bodies attempted to address this problem by establishing fault detection and diagnostic functionality for HVAC equipment. Confirming whether newly installed RTU/economizer systems meet energy efficiency performance posited under recent Title 24 requirements is, therefore, critical.

PURPOSE

This PG&E Code Readiness *RTU/Economizer Analysis and Field Assessment* ("the Study") investigated whether Title 24 compliance modeling rulesets for RTU/economizer HVAC systems adequately reflect real-world performance of such systems installed after July 2014 in California.

STUDY DESCRIPTION

The Study began with a literature review of the basic technology and market data on the application of RTUs with economizers to help develop the research plan. Commercial saturation studies were the primary source for the market saturation and energy consumption in California provided below. Additionally, the Study Team reviewed several field studies on RTU/economizer performance, including reports for California Energy Commission (CEC) Public Interest Energy Research (PIER) projects and studies from the Western Efficiency Cooling Center at the University of California (UC) Davis. In addition to providing useful, but dated, market saturation data, these field studies documented many performance problems associated with RTU/economizers in West Coast markets. The more recent DNV GL Impact Evaluation of 2015 Upstream HVAC Programs (HVAC 1),[2] however, suggested that this performance situation had improved somewhat following enhancements

[1] Itron, Inc.,2014.

[2] DNV GL, 2017(1).

in Title 24 2013, including Fault Detection and Diagnostics (FDD), warranty requirements and acceptance testing, though significant underperformance appeared common.

The literature review confirmed that real-world energy efficiency of newer, multi-stage RTU/economizer systems in California climates was not well understood. As a result, the Study Team hypothesized that the effectiveness of economizer operation in real-world settings may be significantly lower than expected. This Study sought to answer research questions related to:

- The inputs used for compliance modeling tools for Title 24 relating to RTU/economizer systems.
- How performance curves for installed RTU/economizer systems compare with the performance curves assumed in Title 24 compliance software.
- The frequency of problems related to economizer setpoints, damper range of motion, temperature sensors, and outdoor airflow for RTU/economizer systems installed since 2014.
- The implications of economizer underperformance with respect to energy use, load shapes and system coincident peak in California climate zones.
- The efficacy of current acceptance tests and opportunities for improvement related to physical and procedural compliance for RTU/economizer systems.

METHODS

This Study organized research into four main elements. In the first element of the Study, the Study Team documented the key assumptions for the RTU efficiency performance (compressors, fans, etc.,) embedded into California Building Energy Code Compliance (CBECC) Title 24 compliance software, CBECC-com, and EnergyPlus and whether the key assumptions appeared to be appropriate for current conditions. The Study Team simulated selected energy model prototypes in several California climates in EnergyPlus to compare assumptions for the direct-expansion (DX) performance curves adopted by the CEC in Title 24 2019 to additional sets of performance curves commonly used in DX performance simulations. In California's mild climates the impact of economizers on heating energy use is so minor that is appropriate to continue to focus on cooling impacts.

The second element of the Study involved field inspections of RTU/economizer performance, the methods for which expanded on the HVAC 1 study's functional performance test (FPT) methods. The Study Team conducted site visits across California's greater Bay Area (Climate Zones 3 and 4), the Sacramento area (Climate Zone 12) and Central Valley (Climate Zone 13). The Study Team examined a sample of RTU/economizer systems sized between 5 and 15 tons and installed since July 1, 2014, to assess the frequency of failure or underperformance of newly installed RTU/economizers nominally compliant with Title 24 2013 or later.

In the third main element of the Study the Study Team, using EnergyPlus 9.4, modeled with proxy inputs for selected RTU/economizer operational faults and controller programming errors. It analyzed the results to quantify how estimates of energy use in commercial buildings that utilized RTU/economizers would be impacted based on each of the operational fault and programming error findings of the Field Study. The Study Team post-processed hourly modeling results using Time Dependent Value (TDV) multipliers used in California energy code compliance from the 2022 energy standard to assess reductions in compliance that would result from the operational faults and programming errors. The Study Team combined results of all simulations to estimate the average change in energy efficiency of an RTU/economizer compared to a fully operational system. The Study Team then further extrapolated the operational fault and programming error frequencies found in the field assessment portion of the Study with findings from the HVAC 1 study. This extrapolation was done due to the small sample size of the Study to more conservatively estimate typical RTU/economizer performance in California compared to the fully functional and correctly programmed RTU/economizer assumed in Title 24.

The last main element of the Study assessed acceptance testing methods. During the Study site inspections, the Study Team gathered relevant design and compliance documentation such as mechanical schedules; Title 24 compliance forms; Title 24 mechanical acceptance forms; or test, adjustment, and balance reports. The Study Team reviewed documentation in the context of the findings at each site to assess how well the acceptance testing process identified operational faults and programming errors, as well as Title 24 compliance, and whether improvements to the acceptance testing protocols and forms were apparent.

MAJOR FINDINGS

1. Current reference DX HVAC system performance curves seem appropriate, though some concerns remain about the representativeness of the low part-load efficiencies of the reference curves.
2. There was a high incidence of operational faults and programming errors due to poor installation practices in newly installed RTUs/economizers that resulted in significantly worse performance than expected. Of the 26 systems tested, the Study found only three systems correctly installed and programmed to provide the expected amount of economizer cooling. The Study's key field observations were:
    a. Of the units with installed economizers, only 77% of units had a functional damper that could modulate in response to outside and mixed air sensor readings if there was a sensor connected.
    b. Only a slim majority of units (54%) met Title 24 minimum fresh air requirements, which raises the risk of occupant comfort, productivity, and health safety problems.
    c. Of the 25 units with active controllers, the installation of mixed air sensors was correct on only half of the units.
    d. Seventeen out of 26 units had economizer programing errors such as non-compliant setpoints or a fully closed minimum damper position setting
    e. While economizer controllers met the system status and fault reporting capability requirements, they did not typically comply with the notification requirements. Installation and commissioning errors not addressed during installation of RTU/economizers continue to persist a year later, presumably for as long as the unit continues to function normally.
    f. Building inspectors did not appear to be enforcing acceptance testing requirements; if inspectors used the Title 24-2013 and 2016 MCH-05 acceptance test forms as intended, the observed operational faults and programming errors

would not be present in this Study's sample. The Study Team believes that increased compliance stringency in Title 24-2019 may mitigate the problem where acceptance testing occurs.

3. The RTU and economizers observed in the Study met the controller capability and the damper equipment requirements of the code. Nearly all the compliance issues were due to installation errors. The only errors linked to manufacturers are the installers' failures to correctly reset outside air high-limit setpoints from the manufacturers' default values, though it must be noted that specific economizer controller high-limit default setpoints are not a Title 24 requirement.
4. The Study suggests that, on average, operational faults and programming errors increased the expected RTU/economizer electrical cooling energy by 34% and 11%, across the population of recently installed, single-speed and two-speed RTU/economizers respectively, compared to the expected performance assumed by the CEC for new construction. The difference is much larger than this average in some climate zones and for some building types. The incorrect baseline assumptions make it appear that the energy savings of alternative HVAC technologies are lower relative to the RTU/economizer than is the case. This incorrect baseline disincentivizes the selection of improved technologies because their cost-effectiveness is underestimated.

RECOMMENDATIONS

The Study Team offers the following recommendations based on the findings:

1. Code compliance rule sets for RTU/economizers in the energy code simulation compliance option and the prescriptive compliance pathway allowances in the energy code yield better energy efficiency than is realistic in California.

   Recommendation: Simulation rulesets should be adjusted to reflect a deration in the efficiency of RTU/economizer systems to levels found by the Study.

2. Simulation representation of part load performance of RTU/economizer systems for both single-speed and two-speed RTU must continue to be advanced to accurately represent the available products as well as changes or improvements being implemented.

   Recommendation: Perform laboratory and field investigations to determine how typical RTU/economize systems operate at lower part-loads. The differences in internal componentry and controls that drive these differences need to be understood to ensure that performance curves relied on for compliance purposes reasonably reflect the part-load performance of RTU/economizers in California. Based on the findings of this additional investigation the performance curves used by CBECC-Com may need to be adjusted to reflect typical part-load performance better.

INTRODUCTION

PURPOSE AND SCOPE OF THE PG&E CODE READINESS PROGRAM

PG&E's Code Readiness Program supports the development, adoption, and implementation of California's building energy codes through long-range planning and data collection. The program works backwards from long-term climate and energy goals to identify key regulatory opportunities within California's building energy codes and standards framework, then develops strategies to fill data gaps and overcome obstacles to successful adoption and implementation of those regulations. The Code Readiness Program focuses on energy performance, cost-effectiveness, feasibility, and code compliance data to support regulatory advocacy. In addition to its primary focus on field data collection, it works with trade allies to ensure that the market can meet key equipment features and functionalities that will be needed to achieve codes and standards goals and deliver statewide energy and carbon savings.

Collecting field data to inform future energy codes is a key strategy to achieve cost-effective energy savings that persist in buildings long after design and initial construction. Field data better informs energy model inputs to represent actual building operating conditions and HVAC equipment performance more accurately. Building energy codes have historically relied heavily on theoretical energy simulations to inform cost-effectiveness analysis. Realistic performance data is critical for informing cost-effectiveness analysis for code requirements.

GOAL OF STUDY

The Study's goal was to investigate whether Title 24 energy code compliance requirements and energy simulation rulesets for RTU/economizer systems adequately reflected real world performance in California climate zones and make recommendations based on the investigation findings. The Study used research and field observations to inform these recommendations about updating the RTU/economizer system (the HVAC prescriptive standard system baseline for many buildings) compliance requirements and energy simulation rulesets used by energy performance compliance software.

BACKGROUND

In recent years, the evolution of the feature set and performance of typical RTU/economizer systems in California, ubiquitous on many types of small and medium sized commercial buildings, is due to technology development, federal appliance standards, and state building codes. A variety of studies on RTU/economizer systems installed during the last two decades suggests average real-world performance falls short of expectations. The real-world performance of newer multi-stage RTU/economizer units is not well documented for California climate zones, yet the presumed performance of this equipment serves as baseline in Title 24 and building models. It is not clear to what degree more recent technology, standards and building code enhancements have improved the situation.

RTU/ECONOMIZER MECHANICAL SYSTEM OVERVIEW

Space conditioning and ventilation energy consumption is a significant portion of annual energy consumption in existing California office buildings.[3] While past building code measures (notably in envelope and lighting measures) achieved energy savings, California needs enhanced mechanical HVAC systems savings to meet its 2030 nonresidential Zero Net Energy goal.

Typically, RTUs modulate the intake of outdoor air and come equipped with airside economizers, providing ventilation required by building codes, as well as cooling savings of 10-60% depending on climate zone and building type. Figure 1 provides a schematic of a typical system that provides heating and cooling as well as an outdoor air economizing function (economizer) that introduces fresh air into the building airstream for ventilation purposes.

[3] Itron, Inc., 2014.

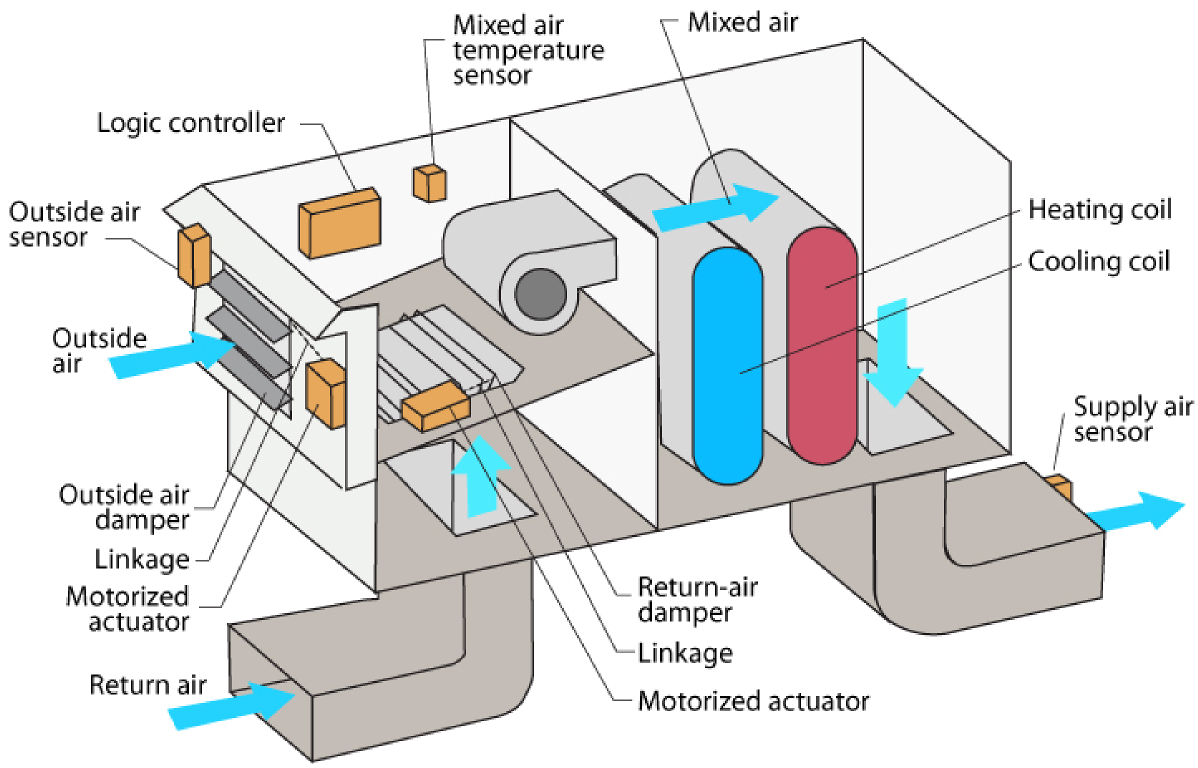


FIGURE 1: CONCEPTUAL DEPICTION OF RTU/ECONOMIZER SYSTEM[4]

ECONOMIZER SYSTEM DESCRIPTION

As shown in Figure 1, an economizer system consists of a controller, a pair of outside and mixed air sensors and an actuator-driven outside air damper system.

1. **Economizer Controller:** An economizer controller contains program logic that calculates a theoretical damper position based on incoming outside and mixed air temperature measurements. The controller then converts the digital damper value into a low-voltage signal which is sent to a mechanical actuator.
2. **Actuator:** The actuator connects directly to the damper system and physically modulates based on received low-voltage signal from the controller.
3. **Damper System:** Figure 2 shows dampers, which are rotating blades that control the amount of fresh air intake into the unit. **An outside air damper** brings in fresh air. It links to **the return air damper** for reverse acting action, i.e., if outside is 100% open, then return is 0% open.

[4] US Environmental Protection Agency, 2021.

The area where the outside and return air meet is the mixed air plenum. After air mixes, it travels through the filters to the RTU's heating and cooling elements.


FIGURE 2: OUTSIDE AIR DAMPERS - 100% OPEN (LEFT) & FULLY CLOSED (RIGHT)

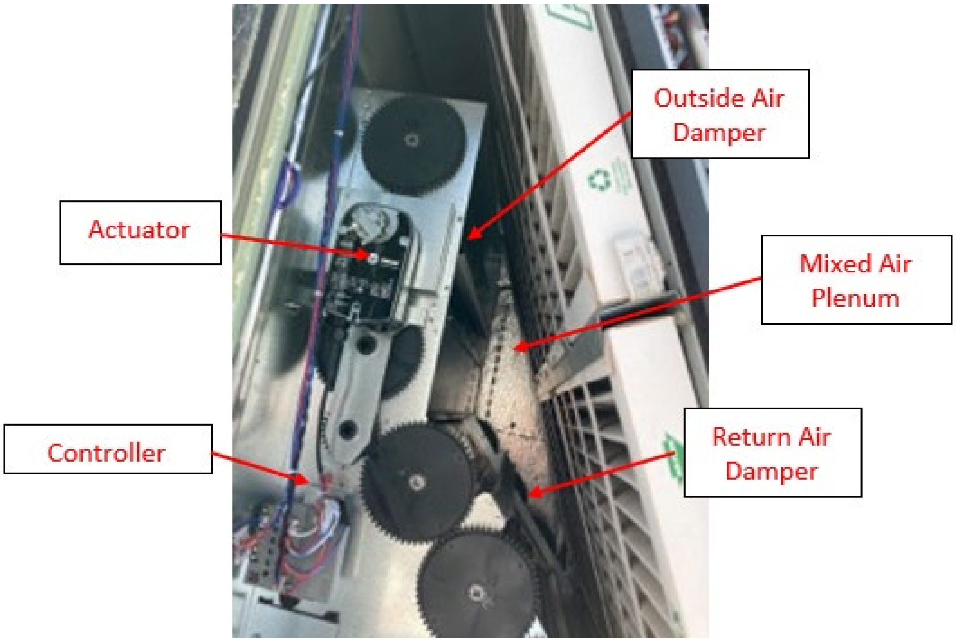


FIGURE 3: TYPICAL ECONOMIZER SETUP – ACTUATOR, CONTROLLER, INTERLINKED DAMPERS AND MIXED AIR PLENUM

4. **Outside Air Sensor:** Outside air sensor measures ambient dry-bulb temperature. In the field, outside air sensor installation is typically under the unit or mounted to the outside air intake where a representative temperature can be measured.
5. **Mixed Air Sensor:** Sensor should be installed in mixed air plenum.

Figure 3 shows the ideal economizer setup.

ECONOMIZER SYSTEM DESCRIPTION SETPOINTS

After installation of the economizer's physical components, the controller must be programmed and integrated into the RTU's primary control board. Following are brief descriptions of the setpoints and modes that must be setup:

1. **High-limit cutoff Point:** The high-limit setpoint determines whether system is in economizer mode. Above the setpoint, the damper should maintain minimum open position or indoor air quality to limit excessive hot air from entering the building. Below the setpoint, the damper should modulate.

   Per Title 24, high limit setpoint may range up to 75°F, depending on climate zone, which Table 1 demonstrates.

TABLE 1: TITLE 24, TABLE 104.4-E, AIR CONDITIONER HIGH LIMIT SHUT OFF CONTROL REQUIREMENTS

Device Type[a]	Climate Zones	Required High Limit (Economizer Off When):	
		Equation[b]	Description
Fixed Dry Bulb	1, 3, 5, 11-16	$T_{OA} > 75°F$	Outdoor air temperature exceeds 75°F
	2, 4, 10	$T_{OA} > 73°F$	Outdoor air temperature exceeds 73°F
	6, 8, 9	$T_{OA} > 71°F$	Outdoor air temperature exceeds 71°F
	7	$T_{OA} > 69°F$	Outdoor air temperature exceeds 69°F

2. **Freeze protection Setpoint:** The freeze protection is the low-limit setpoint. Below this setpoint, the damper should maintain minimum open position to prevent coil freeze. Above setpoint, the damper can modulate; this setpoint value is typically 32°F.
3. **Mixed Air Setpoint:** The mixed air setpoint is the target cooling supply air temperature setpoint when the RTU is in economizing mode (orange line in Figure 4). The economizer controller will modulate the damper to maintain this setpoint (blue line in Figure 4). When the outside air temperature is above this setpoint, the damper is 100% open until the outside air temperature exceeds the high limit shut off beyond which the damper shuts to the minimum position.

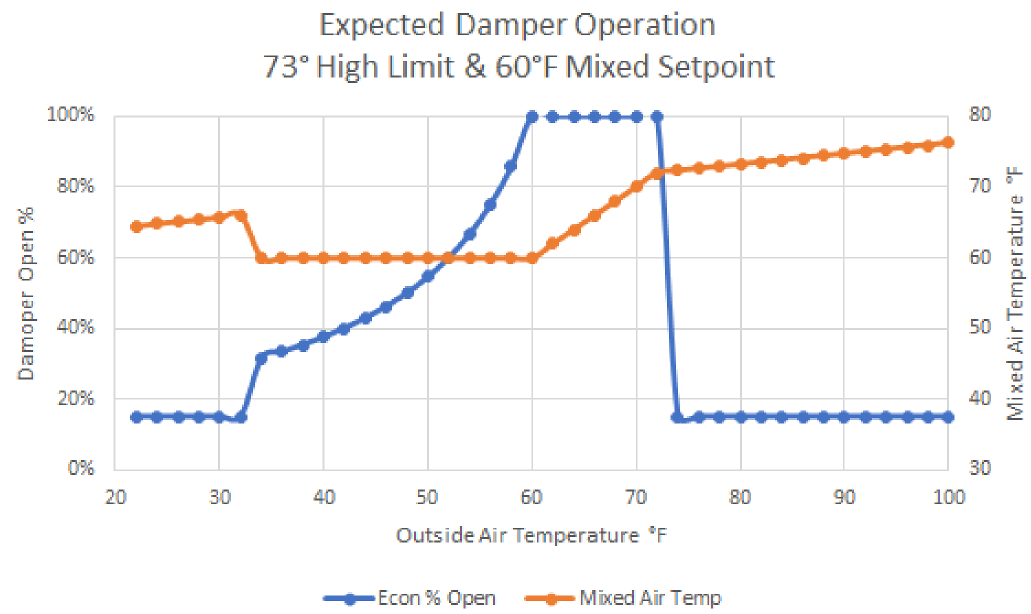


FIGURE 4: IDEAL ECONOMIZER PERFORMANCE

4. **Minimum Open Position:** Per Title 24 code, whenever the unit operates it must provide a minimum amount of fresh air. Only when the unit is off and fan shuts down should the damper shut completely. The fresh air requirements for the area or number of occupants, whichever is higher, determines the required minimum fresh air flow CFM rate. Table 2 shows an example of minimum CFM design calculations from Title 24 mechanical plans.

TABLE 2: TYPICAL MINIMUM CFM DESIGN DALCULATIONS FROM APPROVED TITLE 24 MECHANICAL PLANS

AREA BASIS			OCCUPANCY BASIS			MINIMUM	
G	H	I	J	K	L	M	N
Conditioned Area (ft²)	Min CFM per Area	Min CFM by Area	Number of People	CFM per Person	Min CFM by Occupant	Req'd Vent Airflow (Max of I or L) (CFM)	Complies
1016	0.5	508	42	15	630	630	Y
265	0.15	40	6	15	90	90	Y
345	0.15	52	3	15	45	52	Y
48	0.15	7	1	15	15	15	Y

During installation, the damper system must be field balanced, i.e., correlate the lowest voltage signal to a damper position that equals minimum design flowrate. The highest voltage signal should equal 100% open to meet maximum CFM design flowrate.

MARKET OVERVIEW

The Study Team conducted a literature search to inform the Study's final research plan, including determining the range of equipment to be evaluated. The Study Team deemed California-specific reports, including the California *Commercial Saturation Survey* and the Western Cooling Efficiency Center (WCEC), sufficiently current to inform the plan. The Study Team used the market data to identify the RTU/economizer system sizes applicable for this field assessment.

The *California Commercial Saturation Survey*[5] reported that single-zone HVAC systems are the most common type of HVAC distribution systems, found at approximately 98% of sites and constituted 94% of HVAC units. The survey found that for California, 54% of commercial sites had packaged single-zone HVAC units which represented 59% of the HVAC units found. The UC Davis Western Cooling Efficiency Center found that RTUs serve 70% of light commercial floor area in California and notes that "these packaged systems are ubiquitous because they offer several practical advantages: low initial cost, integration of heating and cooling in a single unit, reliability, availability of trained installers and service technicians, a well-established distribution network, etc."[6]

With almost half of new commercial building space and even more of existing space in California conditioned with packaged HVAC units, packaged RTUs are a major driver and focus of the regulation of energy efficiency in commercial buildings.

The California Commercial Saturation Survey showed that the incidence of RTUs is consistent across commercial building size except for the very small commercial buildings, which Table 3 demonstrates.

[5] Itron, Inc., 2014.

[6] WCEC, 2012.

TABLE 3: DISTRIBUTION OF COOLING EQUIPMENT TYPE BY BUILDING SIZE[7]

Cooling Equipment Type	Large	Medium	Small	Very Small
Direct Expansion Cooling (DX)	85.7%	82.0%	84.6%	68.9%
Non-Direct Expansion Cooling	10.9%	12.6%	6.0%	5.0%
No Cooling	3.4%	5.4%	9.4%	26.1%
SZ DX Cooling Distribution				
Package Single Zone	60.3%	57.3%	61.2%	40.0%
Split Single Zone	5.0%	10.9%	15.2%	11.5%
Package Terminal Unit	2.4%	2.4%	3.6%	13.1%
Mini Split System	5.6%	4.5%	2.3%	4.1%
Other Direct Expansion Systems	12.4%	6.9%	2.4%	0.1%
n	**2,517**	**8,341**	**2,861**	**583**

* **The results presented above have been weighted by site weight.** Totals represent the count of surveyed HVAC units included in the analysis. Large Sites have an annual usage over 1,750,00 kWh, Medium have greater than 300,000 kWh and less than or equal to 1,750,000 kWh, Small have a max annual usage greater than 40,000 kWh and less than or equal to 300,000 kWh and Very Small have annual usage less than or equal to 40,000 kWh.

WCEC notes that, "of the units in the PGE CEUS database, 70% are below 7.5-ton Single Zone VAV Systems"[8]. Citing research from New Buildings Institute in 2003, WCEC depicted the population of RTUs by unit volume and by aggregate capacity in California. Figure 5 and Figure 6 show that the most popular packaged DX RTU capacity is 5-tons; units between 4 and 20-tons represent about 65% of the stock constituting over 70% of the entire RTU capacity installed[9]. The difference between Figure 5 and Figure 6 is that Figure 5 reflects the percent of number of units at each capacity. Figure 6 shows the percent of total capacity at each size. So, while there are fewer 15-ton units (only 5% of total RTUs), that number of RTUs represents closer to 10% of installed RTU capacity. These data informed the decision to select 4.5 to 15-ton as the capacity range targeted for site visits.

[7] Itron, Inc., 2014.

[8] WCEC, 2012.

[9] Jacobs et. al., 2004.

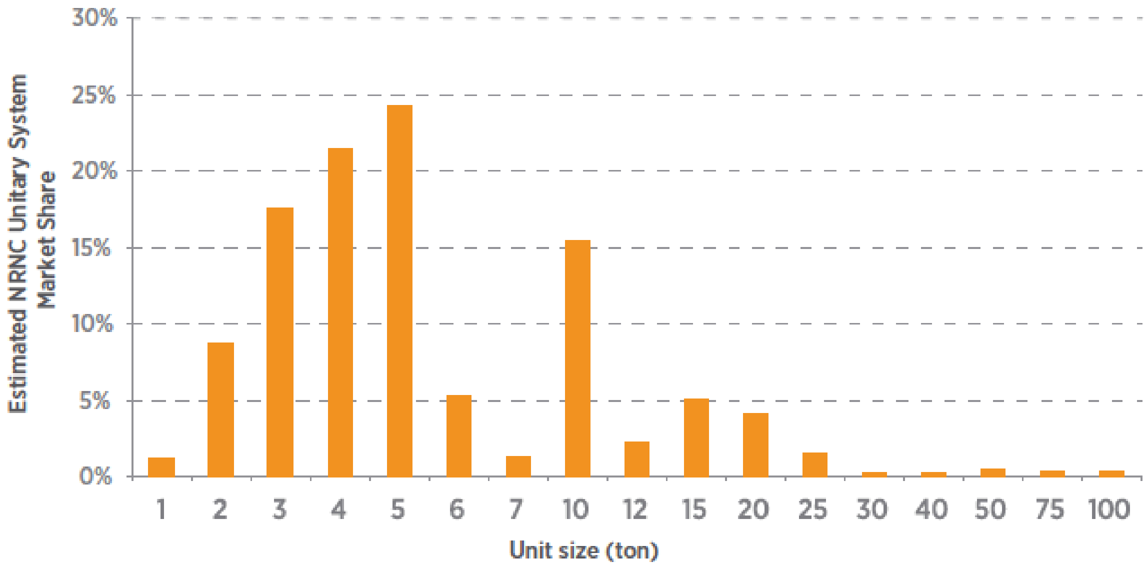


FIGURE 5: PACKAGE HVAC CAPACITY DISTRIBUTION BY UNIT SIZE OF SYSTEMS IN CALIFORNIA[10]

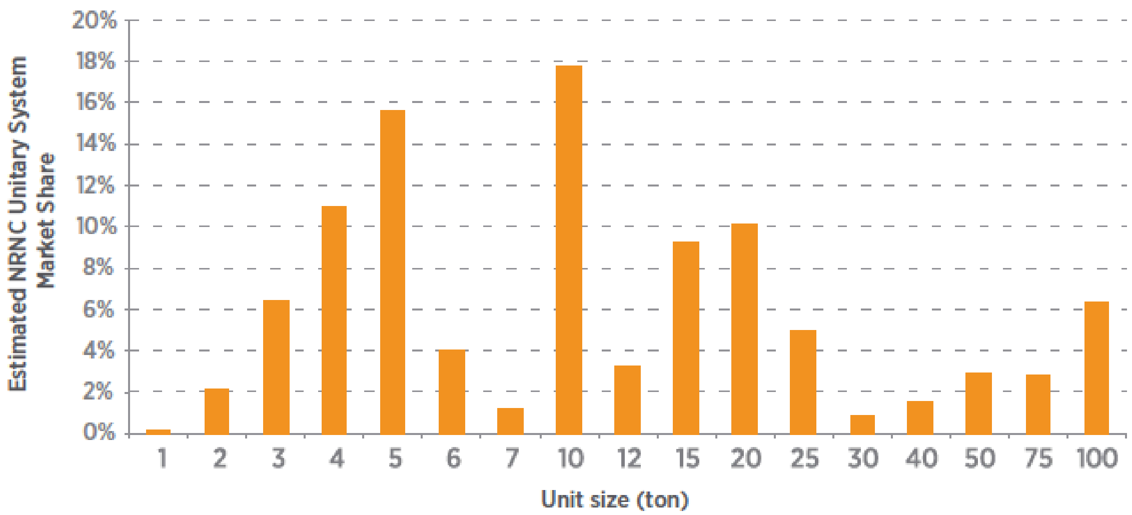


FIGURE 6: PACKAGE HVAC CAPACITY DISTRIBUTION BY INSTALLED CAPACITY[11]

OVERVIEW OF DOCUMENTED PERFORMANCE ISSUES

Previous studies referenced in this Study contain a detailed overview of common RTU economizer performance issues. As Peter Jacobs, et.al., describe: "small commercial HVAC

[10] WCEC, 2012.

[11] WCEC, 2012.

systems are notorious for consuming more energy than necessary… several studies have confirmed poor performance".[12] Peter Jacobs documented that economizers fail to perform as intended in over 60% of installations even in the case of newly installed systems (two years old or less). Improper charge and other controls problems are almost as frequent. These findings in part led to the adoption of Title 24 FDD requirements for packaged HVAC over 54,000 Btu/hr. A 2012 WCEC Study further described the frequency of RTU problems in the field and described the problem of over-sizing RTUs.[13]

The California Public Utilities Commission sponsored a report by DNV GL to collect onsite data on participating units to make adjustments to key technical assumptions that affect the calculation of energy and demand savings. DNV GL found that only 73% (+/-8% at 90% confidence) economizers were functional in its evaluation of the California Investor Owned Utility Upstream HVAC program for 2015-year installations all of which were new, and mostly high efficiency units. Another 18% could not be determined as fail or pass and 27% had failed. It is unclear whether that implies that closer to 27% or 45% failed if one eliminated uncertainties of inspection. If the latter case proved correct, given that these are new installations, the DNV GL study suggests that economizer performance did not improve much as a result of enhancements to Title 24. If the former case is more accurate, it suggests that on average there is still a significant loss of efficiency.

[12]Jacobs et.al., 2004.

[13] WCEC, 2012.

PURPOSE OF STUDY

The Study investigated whether Title 24 compliance modeling rulesets for RTU/economizer HVAC systems adequately reflect real world performance in California climate zones. Changes in Title 24 can address installation, commissioning, and acceptance testing that support modeling rulesets.

Packaged RTUs, which constitute a majority of packaged HVAC, are a major driver of and opportunity for energy efficiency in commercial buildings. Typically, RTUs with capacity above 54,000 BTUh must modulate the outdoor air flow and come equipped with airside economizers. Depending on the climate zone, economizer cooling savings can be very significant (10-60%) when operating according to specifications. The CBECC-Com model presumes full achievement of air economizer savings. The result is that the Title 24 baseline for many building types assumes significantly more savings than is being achieved. The challenge is to determine to what extent RTU/economizer underperformance compromises energy efficiency presumed under Title 24.

Past studies (prior to implementation of the 2013 cycle of Title 24) attempted to estimate the energy efficiency penalties of field performance problems. The WCEC compiled various studies and research to estimate efficiency. The DNV GL *Impact Evaluation of 2015 Upstream Program* documented that "considerable savings potential is not being realized because many economizers for unitary systems installed through the program are not functioning properly."[14] Through a literature search and conversations with industry experts, the Study Team did not find other field studies addressing field performance of equipment installed after 2013 (i.e., with FDDs, commissioning, and acceptance testing required by Title 24 2013). It was not clear whether the implementation of 2013 and 2016 provisions in Title 24 materially mitigated these problems in practice.

IDENTIFY ENERGY EFFICIENCY IMPLICATIONS OF RTU/ECONOMIZER UNDERPERFORMANCE

The performance of newer, RTU/economizers in terms of operational efficiency is not well established in California climate zones and effectiveness of economizing in real world settings may still be significantly lower than expected. This Study aims to address two issues related to the performance of new RTU/economizers as represented in current California's Title 24 Part 6 energy codes.

1. Evaluate Current Energy Modeling Part-Load Performance Rulesets of RTU Cooling Systems.

The performance software used for non-residential building compliance uses a default set of performance rules which govern the control of RTU systems, specifically the air-conditioning compressors and in-unit fans. The performance rules which specifically represent the cooling system, in RTUs the DX-cooling element, rely on a set of system performance curves which adjust the unit's operational efficiency based on part-load and ambient indoor and outdoor conditions. Since the original adoption of the current set of performance curves by the Title 24 energy standard in 2013 with the shift to CBECC-Com and EnergyPlus as the basis for

[14] DVL-GL, 2017(1).

performance compliance, new additional data sets are now readily available for use in the simulation of DX-cooling elements used by the Department of Energy (DOE) in system evaluations and by different national laboratories conducting energy modeling research projects. The Study included a review of the currently available DX-cooling performance curves publicly available for their impacts on energy use and peak demands compared with defaults used today. The review focused on evaluating how these curves differ and impact the annual energy of RTU systems.

2. Economizer Performance Issues.

Properly functioning economizers are currently the foundation of commercial building energy standards and the baseline against which energy efficiency of alternate HVAC systems are assessed. Failure to account for endemic underperformance of some economizer components in this baseline could, therefore, result in market underinvestment in alternate HVAC technologies and lost energy savings potential for building owners and for California as a whole. In fact, field studies since the late 1990s reported that RTU outdoor air economizers are prone to functional failure and underperformance starting at the time of installation. It is not clear to what extent new RTUs installed with FDD continue to experience the common early and frequent failures and underperformance as experienced prior to the newer requirements in Title 24 2013.

The Study involved a number of research elements which included:

- Summary of basic market data regarding the saturation of RTU/economizer systems and past performance research through a literature search.
- Documentation of current Title 24 ruleset and Alternative Calculation Method default inputs for simulating RTU/economizer systems controls.
- Energy modeling of RTU/economizer systems with alternate equipment performance curves compared to the current defaults.
- Assessment of current frequency and modes of failure or underperformance of installed RTU/economizers nominally compliant with Title 24 2013 or later.
- Assessment of how well the FDD component communicates failure messages to occupants or operational management and what the outcomes of this communication are.
- Parametric energy modeling analysis of the impacts on a Title 24 RTU/economizer system based on observed configurations and functional performance of RTU/economizers from field performance evaluations.
- Identification of opportunities to improve Title 24 performance simulation rulesets for RTU/economizer system controls to reflect the reality of underperformance found in field investigations.
- Assessment of the adequacy of the acceptance testing protocols for RTU/economizers as reflected in Title 24.

SCOPE OF STUDY

The Study sought to answer the following research questions:

1. With respect to current energy code compliance rulesets and performance curves of RTU/economizers:
   a. What are the default set of efficiency allowances and control sequences for RTU/economizer systems?
   b. What performance curve sets are publicly available for representing DX-cooling components in the code compliance software (EnergyPlus/CBECC-Com)?
   c. How do different performance curve sets impact annual energy, peak demand, and code compliance in a typical building energy model?
   d. How would extreme weather impact a typical building's annual energy, peak demand, or code compliance based on the different performance curve sets with an RTU/economizer system?
2. For RTU/economizer systems installed since mid-2014 in compliance with economizer hardware requirements of Title 24 2013 or later, in what proportion of a representative selection of building sites are one or more of the following problems found (and how severe are the problems, if applicable)?
   a. Programming Issues: Are economizer setpoints compliant with Title 24 requirements? If not, do they result in sub-optimal downstream effects on the damper activation?
   b. Damper Operation: Is damper range of motion limited by equipment failure?
   c. Temperature Sensor Installation: Are temperature sensors missing or incorrectly connected or located; do temperature sensors fail; or are temperature sensors calibrated incorrectly?
   d. Minimum Outdoor Ventilation: Are observed outdoor airflow rates through the economizer calibrated correctly and meeting health and safety requirements?
3. What are the energy savings implications of the underperformance of economizers with respect to energy use, load shapes and system coincident peak demand?
4. Are current acceptance tests uncovering poorly set up systems? What gaps and opportunities for improvement exist in the acceptance test enforcement procedure related to physical and procedural compliance?

METHODS

STUDY DESIGN

The Study had four main elements:

Study Design Element 1. Review of Energy Modeling Performance Rules of RTU/Economizers

With respect to the RTU efficiency performance (compressors, fans, etc.) the Study Team documented the key assumptions embedded in the Title 24 compliance software (CBECC-Com and EnergyPlus) and other sets of performance curves publicly available used to simulate the same types of components. Specifically, the Study Team investigated the following:

- Energy code allowances for fan system efficiency and pressure allowances for RTU/economizers, single-speed and two-speed systems.
- Publicly available performance curves for DX-cooling elements used in EnergyPlus and the default set of curves used in the compliance software (CBECC-Com 2019).
- Reviewed the differences in building annual energy, peak demands, and compliance metrics using a prototypical building model.
- The impact on annual energy, peak demand, and compliance metrics of each curve-set under extreme weather conditions by climate zone.

Study Design Element 2. RTU/Economizer Field Assessment

The RTU/economizer field assessment investigated economizer failure and underperformance modes and their frequency in a representative sample of RTU/economizers intended to be compliant with Title 24 2013 or 2016 requirements (which includes FDD, commissioning, and acceptance testing). During each site visit, the Study Team assessed RTUs by running through their control sequences and inspecting the operational status of economizers, in addition to checking thermostat schedules and heating/cooling settings. The Team also conducted interviews with site staff, and when possible, maintenance staff.

Study Design Element 3: Modeling and Summarizing Energy Savings Implications

The primary energy modeling investigation objectives were to estimate the average real-world performance of RTU/economizers relative to how they are modeled in the Title 24 and, to estimate what the market typical building operational energy use would be relative to a building with an operational economizer and to then estimate average energy efficiency degradation based on frequency of operational faults and programming errors.

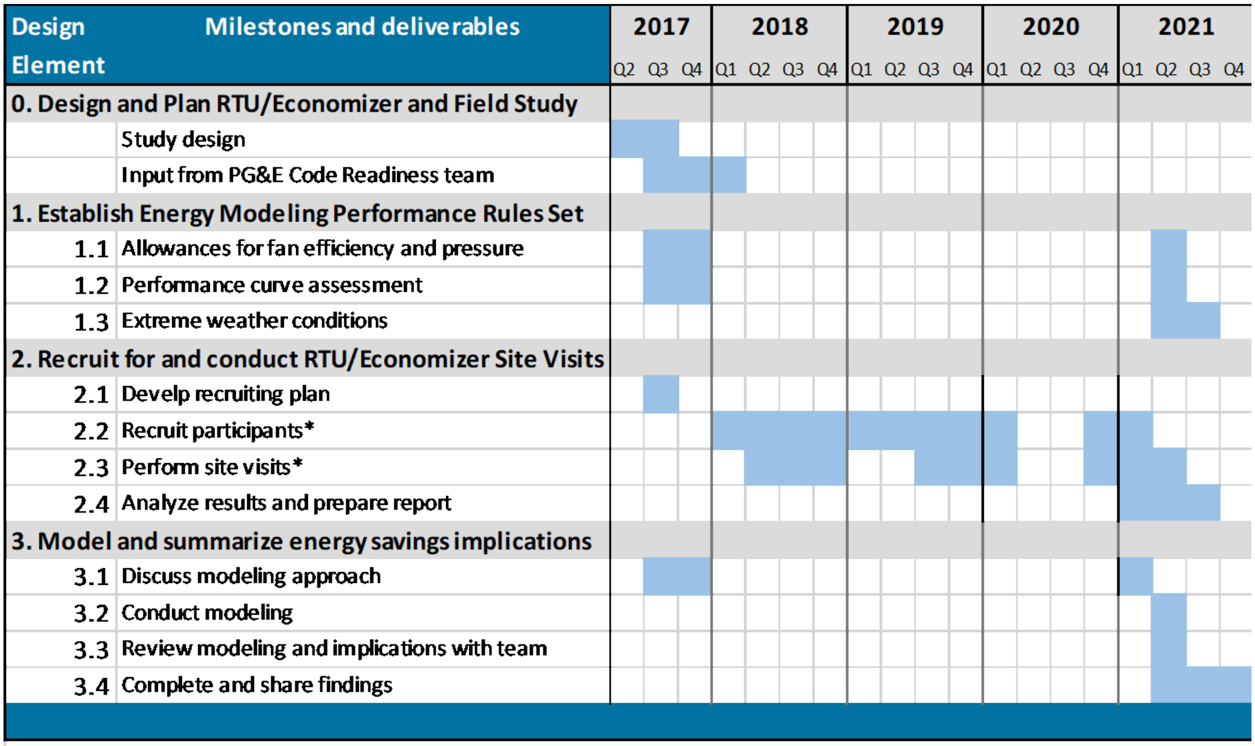
Study Design Element 4: RTU Acceptance Testing

As part of the field assessment, the Study also gathered relevant design and compliance documentation such as: mechanical schedules; Title 24 compliance forms; Title 24 mechanical acceptance forms; or test, adjustment, and balance reports. The Study Team used this documentation to determine whether the unit design and testing complied with Title 24 requirements.

Study Timeline

Table 4 shows the Study timeline.

Table 4: Study timeline



*Recruiting and site visits held on multiple occasions due to wildfires, Pubic Safety Power Shutdowns, and pandemic-related rules.

Study Team and Roles

The Study Team consisted of the following members with respective roles:

- **2050 Partners** coordinated the overall effort, documented the initial historic performance research, and communicated with the team.
- **kW Engineering** developed and implemented the RTU/economizer field assessment and authored the RTU/Economizer Field section of this report.
- **Evergreen Economics** led the Study participant recruitment with call center and outreach using participants identified through city and county building departments and PG&E database searches.
- **Red Car Analytics** investigated the assumptions and rulesets of Title 24 compliance models and modeled updated performance curves and degraded economizer performance identified during the RTU/economizer field assessment. Note that earlier documents describe work by Integral Group, which shifted to Red Car Analytics after key Integral Group staff founded Red Car Analytics.
- **Additional advisors**. Peter Jacobs of Building Metrics Inc. provided input on the Study's design. Jon McHugh of McHugh Energy reviewed the research plan and provided input on FDD and acceptance testing as well as providing overall suggestions.

RESEARCH & ANALYSIS METHODS

ENERGY MODELING RULESET OF RTU/ECONOMIZERS REVIEW

The Study Team conducted a technical review to gather background knowledge on the representation of RTUs in energy compliance, the sensitivity of part-load performance assumptions, and weather data between a typical year or a more extreme year for the impact of energy consumption.

The Study Team reviewed part-load performance of RTUs in simulation software by evaluating how the current California compliance energy simulation software works and what the part-load assumptions are. The Study Team compared this information with other technical resources on alternative part-load performance assumptions, used by other industry agencies including the DOE National Laboratories. The literature review focused on information that has changed in the last 5 to 10 years in simulation of RTUs and how other assumptions impact operational efficiency.

The Study Team reviewed weather data to understand what the current California compliance pathway uses for regional weather data and what changes those regions have seen over the past several years. The Study Team also investigated the impact on RTU performance due to more extreme weather years.

The Study's detailed research methods included:

- Review of the assumptions of DX performance curves adopted by the CEC in Title 24 2019.
- Identification of additional sets of performance curves used in the simulation of DX-cooling simulation objects and evaluation of the annual energy use, peak demand, and code compliance margins compared with the current set.
- Selection of a prototype energy model and a sub-set of California climates to evaluate the impact and simulate the model with all identified curve sets.
- Selection an actual meteorological year (AMY) weather file for a representative California climate zone that represents a more extreme weather year conditions compared with the typical meteorological year (TMY) developed for Title 24 2022 energy code compliance.
- Evaluation of the annual energy use, peak demand, and code compliance margins of each set of performance curves under the current TYM weather conditions and the extreme AMY conditions selected using the small office building prototype and RTU/economizer system in the same sub-set of California climates.

RTU/ECONOMIZER FIELD ASSESSMENT

The Study Team conducted 15 site visits across California's greater Bay Area (Climate Zones 3 and 4), the Sacramento area (Climate Zone 12) and Central Valley (Climate Zone 13). The team examined a total 26 RTUs between 5 and 15 tons, installed since July 1, 2014 (2013 Title 24 effective date). The purpose of the site visits was to:

1. Assess current frequency and failure modes for failure or underperformance of newly installed RTU/economizers nominally compliant with Title 24 2013 or later.
2. Assess how well the FDD component communicates failure to occupants or operational management and what the outcomes are of this communication.

The Study Team also interviewed site staff and, when possible, maintenance personnel for information regarding service scheduling, alarm clearing and general comfort. Table 5 summarizes the inspected sites.

TABLE 5: SITE VISIT SUMMARY

Site	Site Type	City	Climate Zone	Econ Controller	Qualified RTU Quantity	Avg. Size (Tons)
1	Bar*	Sacramento	12	None	0	N/A
2	Gymnasium	Stockton	12	Stand-alone	2	12.5
3	Church	Stockton	12	None	1	5
4	Office	Stockton	12	Stand-alone	1	5
5	Gymnasium	Stockton	12	Stand-alone	2	7.5
6	Office	Clovis	13	Stand-alone	1	12.5
7	Conference Rooms	San Jose	4	BMS Integrated	2	6
8	Medical Office	Palo Alto	4	Stand-alone	3	6.8
9	Gymnasium	Davis	12	Stand-alone	3	10
10	Restaurant	Sacramento	12	Stand-alone	2	5
11	Lab Space	Sunnyvale	4	BMS Integrated	1	15
12	Office	Sunnyvale	4	BMS Integrated	3	6
13	Cafeteria	Sunnyvale	4	BMS Integrated	1	12.5
14	Office	San Leandro	3	BMS Integrated	2	6
15	Dorm Common Area	Sacramento	12	Stand-Alone	2	10
				Total Qualifying RTUs	**26**	

* Equipment did not qualify

RECRUITING

The Study Team conducted recruiting to obtain a cross section of dominant manufacturer brands, a distribution of RTU unit sizes, and a mix of small to medium commercial and recreational facilities. The Study aimed for a representative mix of economizer controller types. Table 5 also shows a mix of systems operating with stand-alone RTU and thermostat controls; and some sites with RTUs networked to a larger building management system (BMS).

In addition to striving for a representative sample, the Study Team worked to avoid other potential sampling biases, such as oversampling high efficiency units. Key screening items were:

- Presence of one or more electric-powered, packaged RTUs that would be physically accessible to the Study Team
- RTU(s) installation after July 1, 2014
- RTU size, manufacturer and model
- Economizer manufacturer and model
- Availability of equipment paperwork
- Electronic accessibility of the economizer controller
- HVAC maintenance policy/service contract status[15]
- Economizers working at the time of installation or last maintenance
- Presence of an EMS controlling RTUs

Importantly, the Study Team strived to avoid biasing the sample. For example, a third-party market research firm conducted the recruiting. The Study Team specifically sought to not bias the sample towards facilities with RTU performance problems known to the facility manager (or the Study Team). Due to difficulty with recruiting through a third-party firm, the Study Team directly recruited several later sites to be included in the Study, but never based on known or suspected RTU performance problems.

Field Data Collection and Quality Control Process

Each field assessment site visit consisted of data collection and functional testing. Data collection included general site data, equipment quantities and parameters, observations of equipment condition, and other pertinent information.

Step 1: Interview with Site Contact

After identification of a potential qualified site, the Study Team coordinated site access and logistics prior to the site visit. The Study Team requested pertinent design information such as mechanical drawings, equipment submittals or Title 24 mechanical compliance/acceptance documents from the site contact.

Once on-site, the Study Team asked the site contact basic questions about occupant comfort and RTU system maintenance. The Study Team also interviewed site staff about comfort. When available, the Study Team asked maintenance staff more in-depth questions regarding servicing, alarming and economizing.

Step 2: Qualified Equipment Check

After the initial on-site interviews, the Study Team conducted a series of construction checks which included the following:

[15] The study did not collect information on the RTU/economizer installation company.

- **Qualification check.** Verified RTU tonnage and installation date through nameplate information.
- **Controller check**. If the unit qualified, opened the service and damper access panels to verify installation of an economizer system. Recorded the economizer controller make and model. Checked if the controller was energized and connected to the main RTU control board.
- **Temperature Sensor check**. Checked temperature sensor placement, their connections to the controller, and calibration, (i.e., compared controller temperature displays to field readings)

Step 3: Functional Testing

The Study Team followed the FPT (functional performance test) procedures, attached to this report as Attachment A: Functional Performance Test Procedures. The team designed the FPTs based on Title 24 mechanical acceptance procedures and common industry documents. The Study Team also aligned the functional tests with procedures developed by DNV GL for the *2015 Upstream Program Evaluation*. DNV GL focused on basic damper modulation. The Study Team expanded the test to qualify either integrated or non-integrated economizer operation and measured outside air flowrates during heating and cooling staging modes. The Study Team completed the following functional test procedures in the site visits:

- **FPT 1. Fault Detection and Diagnostic Check.** Looked for any FDDs, first at the thermostat then at the controller display or BMS.
- **FPT 2. Damper Testing.** For each unit, physically overrode the outside air temperature sensor using cooling packs or a heating element to produce a damper response.
- **FPT 3. Integrated Economizers Confirmation.** Created heating and cooling calls at the thermostat to verify unit staging operation. At each stage, noted compressor or gas heating staging.
- **FPT4. Airflow Measurement**. During each stage, measured the flowrate in cubic feet per minute at the outside air intake.

Data Collection Tools and Equipment

Figure 6 lists the equipment used in the field assessment. Figure 7 and Figure 8 show examples of the equipment in use during the site visits. The Study Team took temperature and air flow measurements to verify operating parameters.

Table 6: Equipment used in the field assessment

Parameter	Equipment
Temperature °F at Unit	Spur Scientific w/ Thermocouple
Temperature °F at Discharge Registers	Infrared Gun
Airflow CFM at Outside Air Intake	AirData Multi-meter ADM 880C
Additional tools	Screwdriver
	Rachet Kit

	Cooling Pack / Heating Element
	Camera

FIGURE 7: TYPICAL FIELD TEMPERATURE MEASUREMENTS – SPUR (LEFT) AND IR GUN (RIGHT)

FIGURE 8: AIRFLOW METER

ENERGY MODELING AND ANALYSIS

The Study Team performed energy modeling and analysis to quantify how energy use in commercial buildings that utilized RTU/economizers would be impacted based on the findings of the field assessment. The modeling focused on HVAC electrical energy only as the economizer operations primarily impact cooling and fan energy. Heating, which was provided by natural gas furnaces, was not evaluated in detail as the changes to economizer controls would not directly impact annual heating energy significantly.

The Study Team developed a set of parameters to evaluate changes in energy use using prototype building energy models typically used as part of the California Codes and Standards Energy Enhancement ("CASE") efforts. Categories included:

- Building uses, vintage, and location to reflect the types of buildings using RTUs and represent a sample of applications in California.
- RTU system type to reflect two types of RTU components, one operating at a single speed fan and compressor and one operating with a two-speed fan and compressor.

Table 7 contains specific scenarios for each parameter.

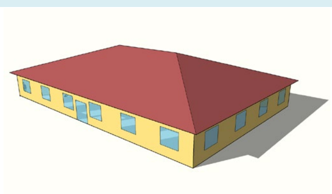
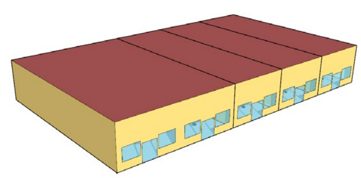
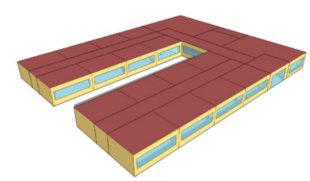
TABLE 7: PARAMETERS AND DESCRIPTIONS USED TO EVALUATE ENERGY USE CHANGES

Category	Parameter	Scenario	Scenario Description
Building and Region	Building Types	1	Small Office
		2	Primary School
		3	Retail Strip Mall
	Building Age	1	New Construction, Built to T24 2022
		2	Pre-1980s Construction (ASHRAE CZ3C)
	Climate Zones	1	CZ3 TMY CEC 2022 - OAKLAND-METRO-AP
		2	CZ4 TMY CEC 2022 - SAN-JOSE-REID-HILLV
		3	CZ6 TMY CEC 2022 - TORRANCE-MUNI-AP
		4	CZ12 TMY CEC 2022 - SACRAMENTO-EXECUTIVE
		5	CZ13 TMY CEC 2022 - FRESNO-YOSEMITE-IAP
		6	CZ16 TMY CEC 2022 - BLUE-CANYON-AP
Systems	RTU HVAC Configurations	1	RTUs >33,000 BTU/hr and < 65,000 BTU/hr Single Zone, Constant Volume, Economizers

		2	RTUs >= 65,000 BTU/hr | Single Zone, Two-Speed Fan, Two-Speed DX, Economizers

A technical literature review informed the selected parameters for these two categories, building use, vintage, location, and RTU system types. The Study Team used building vintage to evaluate new and existing building sets in the first category of parameters. The Study Team used a published set of building prototypes from the University of Colorado in Boulder[16] to evaluate existing building construction sets for a pre-1980s vintage. The source of the building types and base building energy models for each was CBECC-Com 2019 prototype buildings. The Study Team created HVAC systems in EnergyPlus based on the Title 24 ACM requirements for RTUs with economizers to define system efficiencies such as the fan power, compressor efficiency and furnace efficiencies. The Study Team created models in EnergyPlus 9.4 with weather data developed for the 2022 Title 24 energy code cycle, which Table 8 presents.

TABLE 8: SIMULATED BUILDING TYPES WITH FLOOR AREA, THERMAL ZONES AND BUILDING MASSING USED FOR ENERGYPLUS MODEL SIMULATION

	Small Office	Retail Strip Mall	Primary School
Building Total Floor Area sf	5,503	9,376	24,415
Number of thermal zones	5	24	4
Building Massing			

The Study Team selected the number of parameters to provide enough resolution to evaluate changes in energy use across California while also limiting the options to reduce analysis complexity.

For the third category, the Study Team developed a set of "fault parameters" to represent operational faults and programming errors relating to RTU system configuration or control. The Study Team developed discrete scenarios of each fault parameter to reflect the impact and frequency of the observations of the operational faults and programming errors in the field assessment. For example, evaluating how a temperature sensor located as intended versus in a location where the reading would be increased by 1°F, or increased by 2°F, such as outside the RTU unit. Table 9 shows a list of the fault parameters evaluated.

[16] University of Colorado Boulder, Sustainable Buildings and Societies Laboratory, 2021.

TABLE 9: RTU FAULT PARAMETERS INVESTIGATED IN FIELD SITE VISITS AND MODELING ANALYSIS

RTU Fault Parameter	Description
Economizer Control Configuration	The operating range describes how the dampers can function and, how the controls are configured to enable or disable the economizer. Systems may be operating, disabled fully, or controlled to a lower temperature setpoint than required.
Temperature Sensor Configuration	The location or calibration of the air temperature sensors in an RTU can impact how the system will control the economizer in response to outdoor conditions and indoor return air conditions. A system may have this sensor operating correctly or the sensor may be placed in an incorrect location resulting in an incorrect temperature reading.
Minimum Outdoor Air Control Configuration	The minimum outdoor air control of RTUs refers to how the systems dampers and controls are functioning to maintain proper outdoor air. A system may be operating, failed shut with no ventilation, fixed at a set position with no ability to economizer, or limited to a position above the ventilation minimum, increasing the outdoor air provided.

The Study Team simulated prototype energy models in EnergyPlus 9.4. The Study Team post-processed hourly results using TDV multipliers used in California energy code compliance from the 2022 energy standard.

The Study Team combined results of all simulations to estimate the Study's site average energy use and change in energy compared to an operational system. The Study Team documented the frequency of each fault parameter and used it to weight energy use of an average operational system.

TYPICAL BUILDING IMPACT ANALYSIS

The Study Team intended to inspect a generally representative sample of RTU/economizer units for California climates. Due to the scale of the Study, however, it was not expected that the ~30 unit sample would be big enough to produce statistically robust findings. To address this, the Study Team leveraged the more conservative and statistically robust HVAC 1 findings regarding operational fault frequency. The number of sites observed by the HVAC 1 study that were functioning were assumed to be a mix of sites with operational economizers and sites operational with some faults. Furthermore, the HVAC 1 study did not report data regarding economizer programming errors. The Study Team did not find a more statistically robust study reporting the frequency of economizer controller programming errors. In an effort to be conservative given the small sample size for the Study, the Study Team calculated the margin of error (MOE) possible from the limited data. Based on the calculated MOE of the number of sites with simulated faults, the low estimate of the MOE was selected to represent a conservative estimate of sites with degradations in operations.

Applying these two conservatisms, the Study Team calibrated the frequency of the operational faults and the programming errors observed in the Study when assessing the overall average energy efficiency degradation in California reported above. The methodology evaluated the energy impact on each building type, climate zone, and vintage to provide a range of energy impacts to be expected.

RESULTS / FINDINGS

ENERGY MODELING RULESET OF RTU/ECONOMIZERS

The Study Team reviewed current energy modeling software used for energy code compliance of RTU and available publications to answer research question 1:

> Based on current energy code compliance rulesets and DX compressor performance curves of RTUs:
>
> a. What are the default set of compressor efficiency allowances and control sequences for RTU fan systems?[17]
>
> b. What performance curve sets are publicly available for representing DX-cooling components in the code compliance software (EnergyPlus/CBECC-Com)?
>
> c. How do different performance curve sets impact annual energy, peak demand, and code compliance in a typical building energy model?
>
> d. How would extreme weather impact a typical building's annual energy, peak demand, or code compliance based on the different performance curve sets with an RTU system?

KEY FINDINGS

1. The Study found the current reference curve for larger DX systems above 65,000 BTU/hr was about average in operational efficiency compared to the 11 curve sets reviewed and share similar part-load characteristics in how efficiency changes at low and high load factors.
2. The Study found publicly reviewed curve sets used to represent alternate DX part-load efficiency performance, either represent a specific manufacturer or set of components, resulted in a change in energy use from the current Title 24 reference curve set by -9% to +18%.
3. Extreme weather for CZ04 (San Jose, CA) from 2014 had 722 additional hours above 70°F outdoor air compared to a typical year (at 1962 hours above 70°F) resulted in an increase in annual cooling energy for all curves of 31% to 32%.

FINDINGS: PUBLICLY AVAILABLE DX PERFORMANCE CURVES

The Study Team identified 11 sets of DX performance curves from four sources, including the curve sets used as the defaults in CBECC-Com (2019 Title 24 Alternative Calculation Method). The three additional sources included curves used in DOE prototypes, curves

[17] Fan efficiency and fan pressure allowances by Title 24 2019 were maintained since the Study did not capture information on these components.

available in EnergyPlus unmodified software, and curves published paper by NREL on energy modeling part-load curves for small-packaged equipment. Table 10 summarizes the DX-cooling performance curves among these sources. The Study considered *CoilClgDX_CEC_TS* from the CBECC-Com software as the baseline performance curve, which Table 10 shows as curve set 4, and for simplicity the Study used in all generic DX applications and system sizes above 65,000 Btu/hr (5.4-tons). Both single speed and two-speed 5.4 tons units were evaluated; results were similar enough that only single speed results were reported on below for differences between curve sets. Units below this capacity utilized a combination of performance curves and table lookups to calculate the operational efficiencies. The analysis also used this methodology for smaller systems captured as curve set 6.

TABLE 10: DX-COOLING PERFORMANCE CURVES

#Curve Set	Scenario	Curve Set Name	DX Speed Configuration	Source
1	PNNL_Lennox	LennoxStandard10Ton	Single Speed or Two Speed	PNNL-DOE
2	NREL_AC_SS	NREL_AHRI_SS	Single Speed	NREL
3	PNNL_Carrier	Carrier48TM014_12tons	Single Speed or Two Speed	PNNL-DOE
4	CoilClgDX_CEC_TS	DX_Non_PTAC	Two Speed	CEC
5	PNNL_Generic	Unitary_Packagecool	Single Speed or Two Speed	PNNL-DOE
6	CoilClgDXSngl	DXSEER_SS	Single Speed	CEC
7	Goodman CPC060	Goodman CPC060	Single Speed	EnergyPlus
8	York Affinity DNZ060	York Affinity DNZ060	Single Speed	EnergyPlus
9	York Latitude NM060	York Latitude NM060	Single Speed	EnergyPlus
10	York Sunline ZR060	York Sunline ZR060	Single Speed	EnergyPlus
11	York Sunline ZF240	York Sunline ZF240	Single Speed	EnergyPlus
12	NREL-AC_TS	NREL_AHRI_TS	Two Speed	NREL

Each performance curve set included an equation for the following modification for estimating the cooling energy of a DX-cooling object. All curve sets aside from curve set 6 utilized polynomial curves to define the different efficiency factors in EnergyPlus for the DX-cooling object. Curve set 6 utilized a lookup table and relationship to outdoor and indoor conditions were used instead of a polynomial equation for the performance modifier for the energy input ratio (EIR).

Findings: Change in Energy, Power Demand, and Code Compliance of Different Curve Sets

The Study Team evaluated curves by simulating a modified prototype small office building which included economizers on all RTUs and reviewing the frequency of operational efficiency of the DX-cooling objects over the annual run time. The small office consisted of a 5-zone energy model with 4 perimeter spaces and one core space. Figure 9 includes a detailed set of modeling inputs. The Study Team simulated the model in a single climate zone to assess the impacts of different performance curve sets. The Study utilized climate zone 4, represented by San Jose (SAN-JOSE-REID-HILLV weather station) with the TMY weather files developed for the Title 24 2022 code cycle.

The results of the 12 performance curve sets evaluated show the current default CEC curves are in the middle of all other curve sets, with 5 curves showing lower cooling energy use and 6 curves showing higher cooling energy use than the *CoilClgDX_CEC_TS*. The York Sunline ZR240 used the same energy as the baseline. This contrasts with the *York Sunline ZR060* curve from EnergyPlus which used the most cooling energy, 9% more than the *CoilClgDX_CEC_TS* baseline. The *NREL_AC_SS* performance curve used the least cooling energy, 18% less than the *CoilClgDX_CEC_TS baseline.*

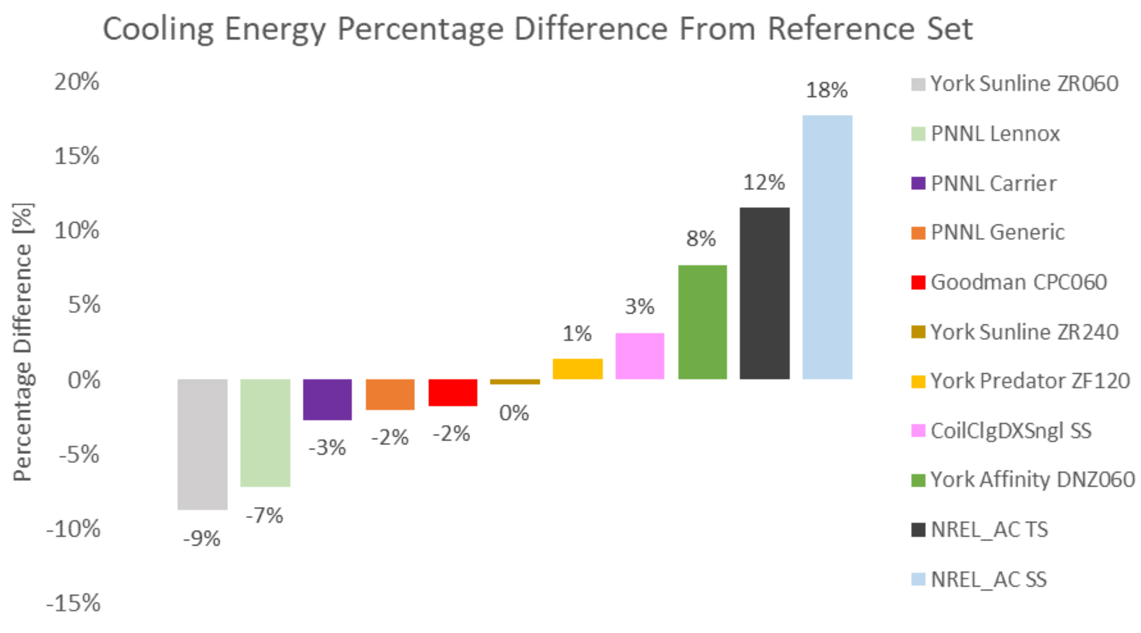


Figure 9: Cooling energy percentage difference from CEC baseline curve

Figure 10 shows more detail and the relationship between the compressor efficiency and the simulated part-load ratio for the RTU units in the small office. The left two columns in blue show the two curves used in Title 24 for two-speed (TS) and single-speed (SS) units and columns three through five show other curve sets. The results displayed are for RTU units configured with single-speed components though they utilize all curve sets, even those noted to be two-speed sets. Results of simulations with two-speed components showed similar findings and magnitude of differences.

Generally, the Title 24 curves have flat efficiencies at all part-loads and a noticeable flat efficiency at low loads, 25% and below. Other curve sets evaluated show a more linear relationship, where at higher part-load ratios the systems have an increased efficiency. For units operating at lower loads more often this difference would become relevant in estimating operational energy needs.

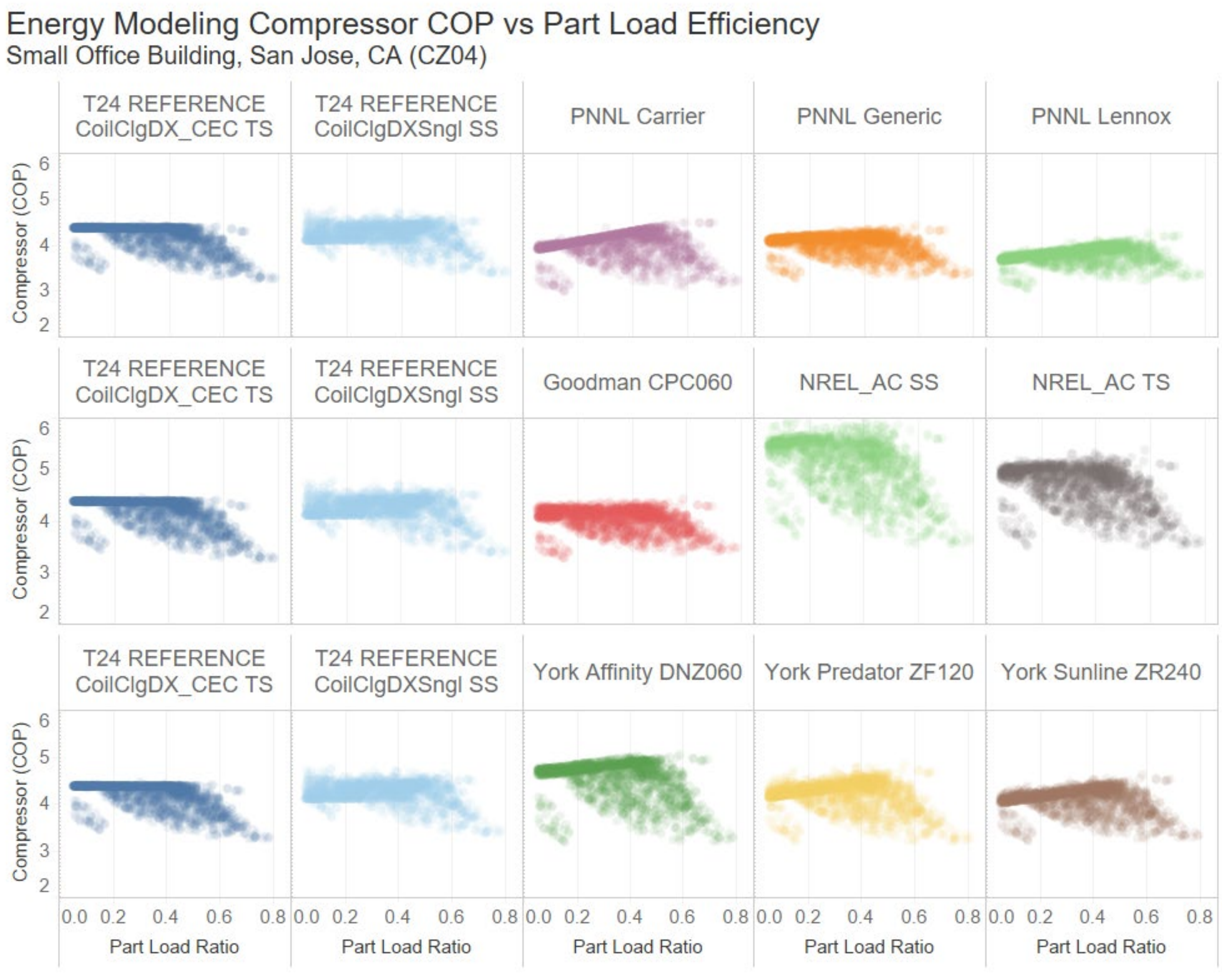


FIGURE 10: RTU COMPRESSOR VS. PART-LOAD RATIO FOR A SIMULATED SMALL OFFICE IN SAN JOSE, CA (CZ04)

Figure 11 shows the same compressor efficiency plotted versus outdoor air dry bulb in the same style for each curve set. Title 24 reference curves for two-speed and single-speed units are shown on each row for visual reference with the others. At outdoor air dry bulb conditions below 75°F, the current Title 24 curves show generally flat efficiencies. A handful of other curves show a similar inflection point in operational efficiency at a lower dry bulb though not all curves.

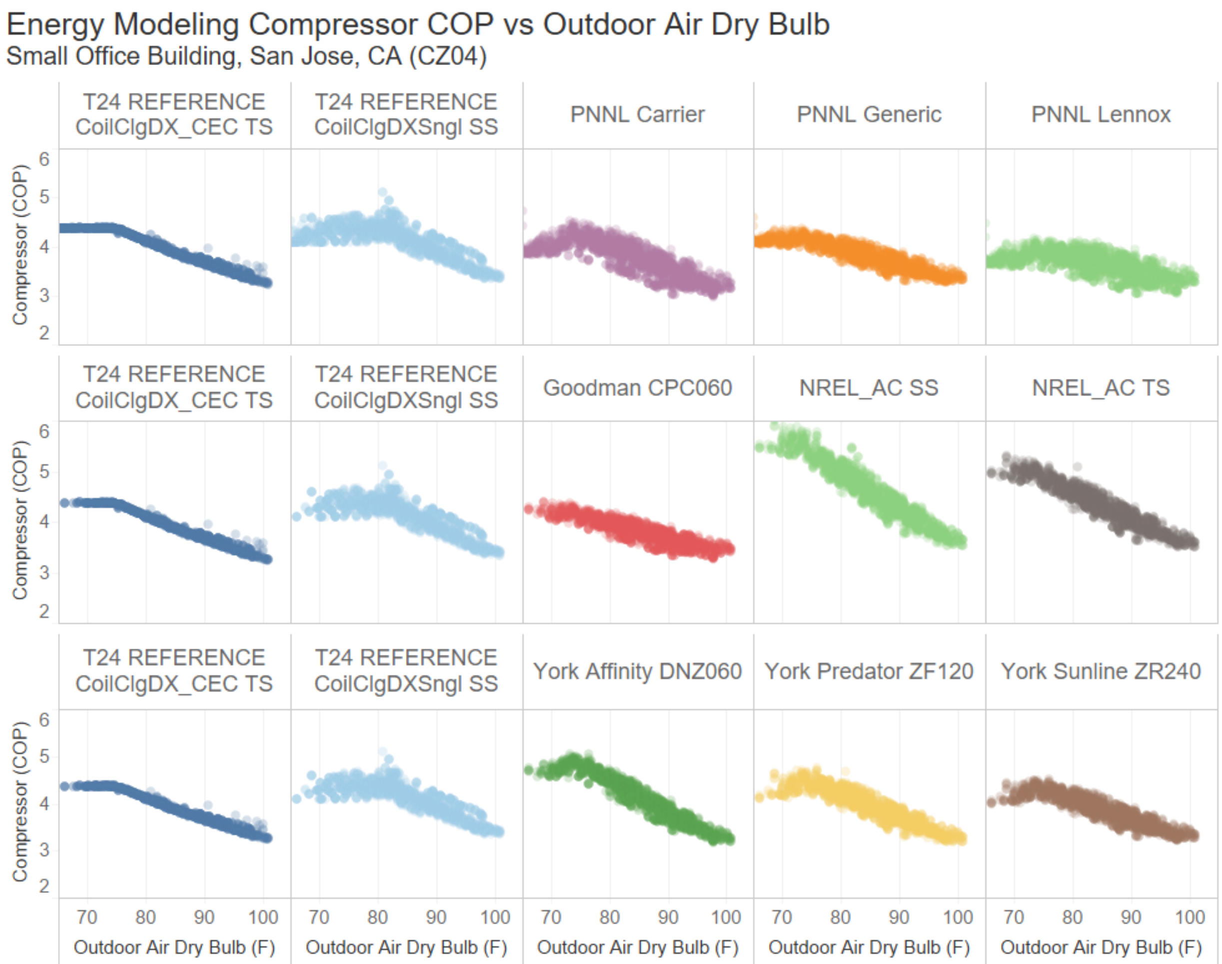


FIGURE 11: RTU COMPRESSOR EFFICIENCY VS. OUTDOOR AIR DRY BULB FOR A SIMULATED IN SMALL OFFICE IN SAN JOSE, CA, CZ04

Reviewing the models in more detail shows how the different curve sets result in changes to annual cooling peak demand intensity. Figure 12 shows that the two blue, Title 24 curves are in the middle of the other curve sets for peak demand intensity in this building model. All curve sets assumed the same rated efficiency based on a code minimum RTU unit. The energy modeling input for efficiency in cooling defines the compressor of the RTU only with regards to thermal efficiency. For units with higher or lower full load efficiency values, where the efficiency of just the compressor can be isolated, the results of these curve sets would adjust linearly, with higher full load efficiencies showing higher values across outdoor air temperatures or part-load conditions.

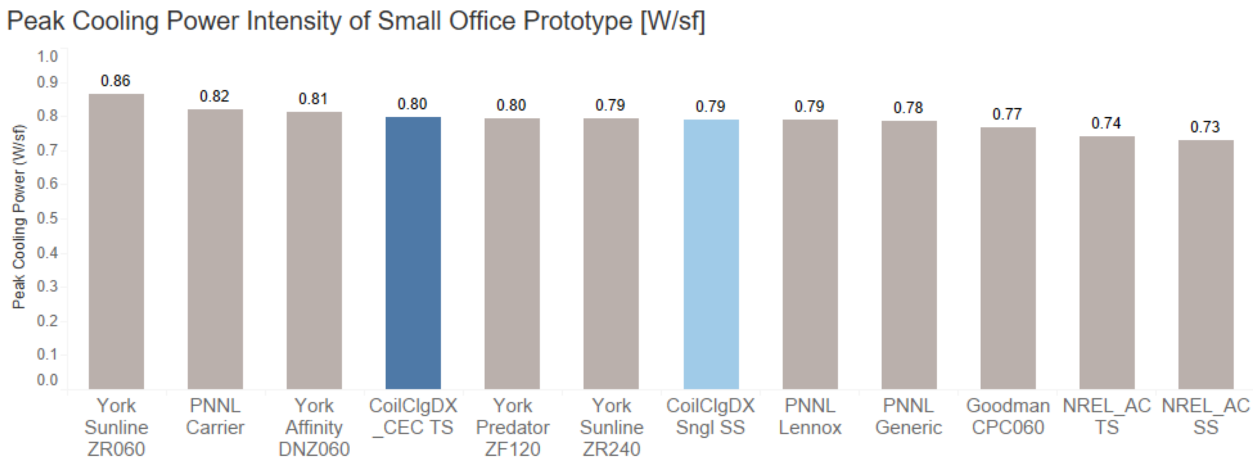


FIGURE 12: PEAK COOLING POWER INTENSITY OF THE SMALL OFFICE PROTOTYPE SIMULATED IN CZ04 IN WATTS/SF

The Study Team also reviewed annual code compliance to understand how the different performance curves would impact a building's ability to demonstrate code compliance. This analysis required the application of a TDV metric used to estimate the life cycle cost of operational energy for buildings. The Study Team applied TDV factors for 2022 Title 24 to the hourly results of the prototype models. Most of the performance curves show a similar value compared to the blue Title 24 default DX-cooling curves in the middle of the distribution at 29 and 27.9 TDV-kBtu/sf. Figure 13 shows these values. Thus, the CEC reference curves appear appropriately representative.

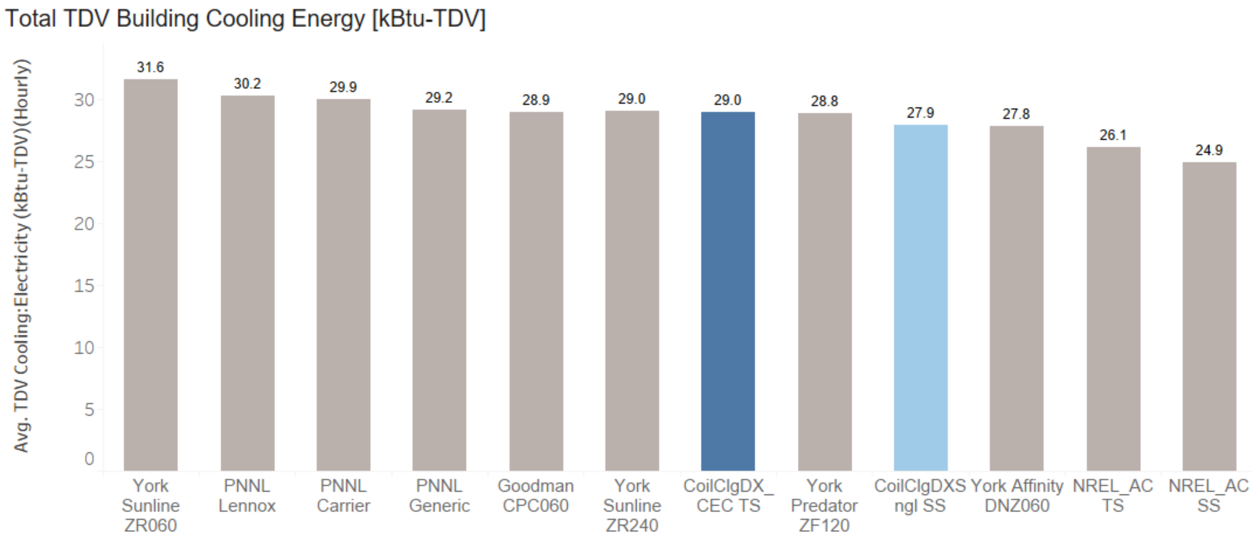


FIGURE 13: ENERGY CODE COMPLIANCE LIFE-CYCLE COST OF ENERGY IN TDV/SF FOR A SMALL OFFICE BUILDING IN SAN JOSE, CA, CZ04

FINDINGS: IMPACT OF EXTREME WEATHER ON DX PERFORMANCE

The Study Team analyzed California AMY weather files from climate zones CZ01 to CZ16 for the years 2014 to 2020 to identify extreme weather data. After analysis, the 2014 climate zone 4 - San Jose (SAN-JOSE-REID-HILLV weather station) data showed the highest median temperature which the Study Team selected for this analysis. Figure 14 shows the weather analysis for CZ04. There was a 37% increase in hours above 70°F (selected as a reference) in 2014 compared to the TYM year.

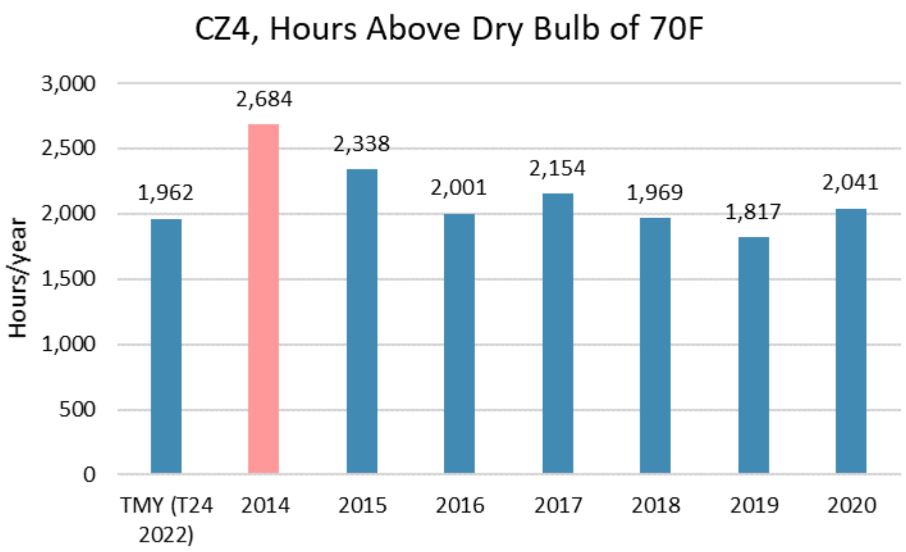


FIGURE 14: WEATHER ANALYSIS OF ACTUAL YEARS FOR CZ04

Table 11 shows the cooling energy for a prototype small office building for the 12 DX-cooling performance curves in climate zone 4. The Study Team simulated the building with TMY weather data and the identified warmer year AMY weather data. Table 11 shows that total cooling energy is 31%-32% higher in extreme weather compared to cooling energy generated with TMY weather data, regardless of the performance curve used.

TABLE 11: TOTAL BUILDING COOLING ENERGY[KWH/SF] OF A SMALL OFFICE PROTOTYPE IN CZ04 COMPARING 2014 AMY AND 2022 TMY WEATHER FILE

Scenario	Total Building Cooling Energy [kWh/sf] with TMY weather file	Total Building Cooling Energy [kWh/sf] with AMY weather file	Percentage Difference
York Sunline ZR060	1.16	1.70	32%
PNNL_Lennox	1.15	1.67	31%
PNNL_Carrier	1.10	1.61	32%
PNNL_Generic	1.09	1.60	32%
Goodman CPC060	1.09	1.60	32%
CoilClgDX_CEC_TS	1.07	1.57	32%
York Sunline ZR240	1.07	1.57	32%
York Predator ZF120	1.05	1.54	32%
CoilClgDXSngl SS	1.04	1.51	31%
York Affinity DNZ060	0.99	1.45	32%
NREL_AC TS	0.95	1.39	32%

NREL_AC SS	0.88	1.29	32%

The Study Team reviewed the daily peak demand over a 24-hour profile for each quarter of the year to identify the impact of more extreme weather conditions would have on RTU/economizer operations. The analysis compared power demand of the building with extreme weather to demand with typical weather, shown in Figure 15. During extreme there was an increase in peak demand in the afternoons over each average day per quarter with the highest increase in peak demand resulting in summer at 9am of 0.1 W/sf. Compared to a typical workstation which can be 0.69 W/sf [18]in an office building for the equipment, the observed peak demand increase of 0.1 W/sf reflected a significant amount of power. The negative impact in Q2 represents a moment where the typical weather simulation showed increased power compared to the extreme weather simulation.

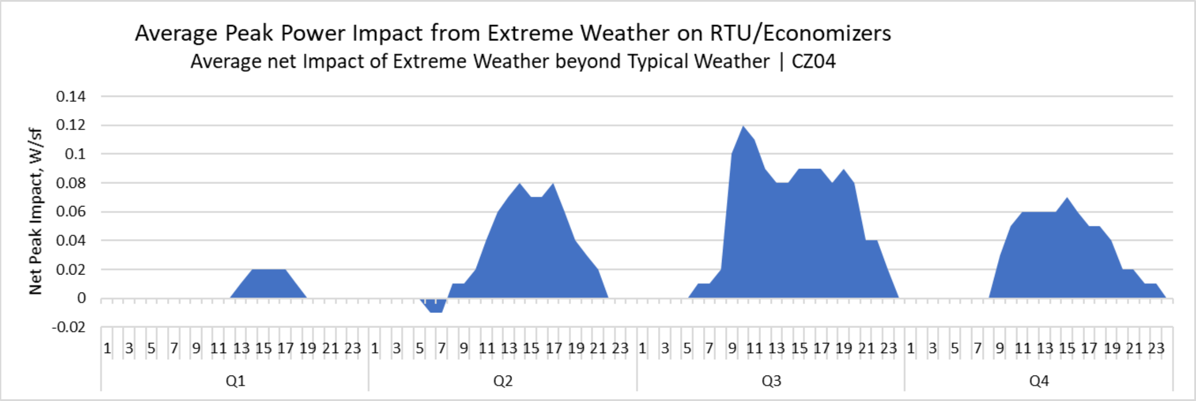


FIGURE 15: ENERGY MODELING NET PEAK DEMAND IN W/SF OF A SMALL OFFICE WITH EXTREME WEATHER (AMY) MINUS THE PEAK DEMAND UNDER TYPICAL WEATHER (TMY), CZ04

[18] 2021 ASHRAE Handbook-Fundamentals, Chapter 18 for a laptop, docking station and 2 screens over 125 sf/workstation.

Operational Field Performance Findings

This section describes findings from the site visits conducted during the field assessment.

Key Findings

The Study aimed to evaluate how well economizers provide free cooling by using outdoor air in lieu of engaging the RTU's compressor compared with Title 24 assumptions. The Study findings indicate that RTU and economizer manufacturers produce Title 24 compliant equipment. RTU and economizer controllers come with factory installed logic, status menus and alarms that meet Title 24 economizer operation and reporting requirements. The Study Team found that most RTUs were in working order, i.e., could provide basic heating, cooling and ventilation in response to thermostat setpoints.

The most frequent issue the Study Team found was that economizer components were not properly installed, and/or the economizer controllers were insufficiently programmed. Title 24 requires an economizer for units over 5-tons installed after 2014. While most units met these Title 24 hardware requirements, one qualified unit did not have an economizer system present, and one had an economizer physically installed but was not connected to the RTU.

Table 12 shows the field assessment findings were that of the 26 qualified RTUs, 25 had an economizer controller physically present within the unit, and 24 of these economizer controllers were wired to the RTU's primary control board.

Table 12: RTU and Economizer Construction Check Summary

Qualified Units	T-Stat Installed and Programmed	Economizer Controller Present	Economizer Controller Wired and Integrated
26	26 (100%)	25 (96%)	24 (92%)

Most importantly, the Study found that due to poor installation and programming setup, a significant number of systems were not economizing as expected. Either the system was not physically capable of modulation due to misplaced, missing, or disconnected equipment; or the system could modulate but programmed settings prevented optimal economizing.

The Study assumption that most units would have their dampers fully or partially open during mild outside conditions (55 – 72°F) was not validated. More often, the Study Team found the damper at minimum open position or closed and the compressor engaged when economizing was expected. The field assessment found the following to be the most common programming and mechanical issues causing sub-optimal performance:

1. Units not programmed for optimized cooling operation in California's climate. Economizer settings either left at factory default settings, or for BMS integrated units, not programmed at all. These settings cut off a significant number of potential economizing hours, and as a result would cause the compressor to operate more often than assumed.

2. Outside air dampers do not modulate due to disconnected economizer controllers or damper actuators. Thus, dampers cannot modulate to 100% open during optimal economizing conditions.
3. Missing or poorly placed temperature sensors. The economizer system cannot perform as intended with missing or misplaced components. These errors limit the economizer controller's modes of operation.

Some units had more than one of the issues listed above. Table 13 shows only 3 of the 26 units had sufficient installation and were programmed with economizer controls to appropriately modulate from their minimum open position to 100% open during mild outside air conditions to provide free cooling. The three sites that passed had the following characteristics:

- All three were BMS integrated units.
- Their high-limit setpoints were programmed near the required high-limit setpoint per Title 24, Table 140.4-E.
- The dampers maintained an open, minimum position.
- The dampers could modulate and maintain intermediate ranges between minimum and 100% open positions.

TABLE 13: FREE COOLING OPERATION SUMMARY

Results	Pass – 3 Units	Fail – 23 Units	
Total Units	Ideal Operation Free Cooling Provided	Programming Errors Sub-optimal settings	Equipment Failure Damper does not move
26	3	17	6

TABLE 14: DAMPER MODULATION SUMMARY

Total Units	Can Modulate	Cannot Modulate
26	20	6

Six units failed because their dampers were at a fixed position. Seventeen units failed because, while their damper could move, they did not modulate open when conditions were optimal for free cooling and instead had their compressors engaged. Table 14 shows that 20 units had some modulation capabilities, where 3 of the 20 had ideal modulation, and 6 were not capable of any modulation.

FAULT DIAGNOSTIC DETECTION FINDINGS

The field assessment also indicated FDD efficacy is limited because alarms are not reported in a clear, actionable way. The Study Team found several sites with active alarm conditions but with no method of reporting them to occupants or maintenance staff as required by Title 24 requirements. Table 15 shows that 14 units failed to meet FDD requirements, resulting in unreported economizer errors. The main issues were:

- Thermostats were not capable of directly reporting economizer alarm faults and they needed auxiliary alarm equipment to comply with requirements. The auxiliary alarms also required additional integration work by the installing contractor.
- For BMS integrated systems, alarm logic was not programmed and thus fault conditions were not reported to maintenance staff.
- Additionally, when alarms met FDD requirements and reported active alarms, occupants often ignored the alarms.

TABLE 15: FDD ALARMING AND REPORTING COMPLIANCE SUMMARY

Total Units	Pass	Fail
26	12	14

Based on conversations with maintenance personnel, the cost of finding and correcting economizer issues in response to FDD alarms on smaller units are not worth the time to fix, and facility managers typically prioritize occupant comfort or equipment reliability over energy efficiency. Thus, economizer operation may be disabled when it interferes with the first two priorities. At some of the Study sites, maintenance personnel said that they were assuming economizer unreliability and disabled the economizer to reduce call backs.

FINDINGS: ECONOMIZER CONTROLLER EQUIPMENT TYPES

This section describes the economizer systems found during the field assessment. These systems were common among several RTU manufacturers (Trane, York, Carrier, etc.).

Economizer controllers come in two basic types: stand-alone and BMS-integrated controllers.

Table 16 summarizes the Study's economizer controller manufacturer, model, quantity findings and BMS integration.

TABLE 16: COMMON ECONOMIZER CONTROLLER MAKE AND MODELS

Make	Model	Quantity	BMS Integrated
Honeywell	Jade	7	No
Johnson Controls	ECO-1001 / SE Control	9	No
Johnson Controls/ Trane*	FEC / ReliaTel	9	Yes

**All BMS controllers found in this Study were Johnson Controls Metasys BMS controllers connected to Trane ReliaTel™ economizer actuators.*

Stand-Alone Controllers: The Jade and ECO models are stand-alone controllers. The controller design is specifically for RTU economizer operation in a self-contained system, i.e., not integrated into a BMS. They come with outside and mixed air sensors, and are factory set with default outside and mixed air setpoints and Title 24 required fault alarms.

The Jade and ECO models only control economizer operation. The RTU's main control board controls all other RTU functions, such as scheduling, heating and compressor operation, and fan speed. An HVAC technician must wire the economizer controller into the RTU board to integrate RTU staging information and program economizing as the 1st stage of the cooling sequence.

Figures 16 and 17 show two common configurations for the ECO and Jade models, respectively. The ECO is always paired with the Smart Equipment (SE) Control board. The SE Control board contains the LCD display that shows all current RTU operating parameters. The RTU board sends signals to the ECO which then sends signals to the damper actuator.

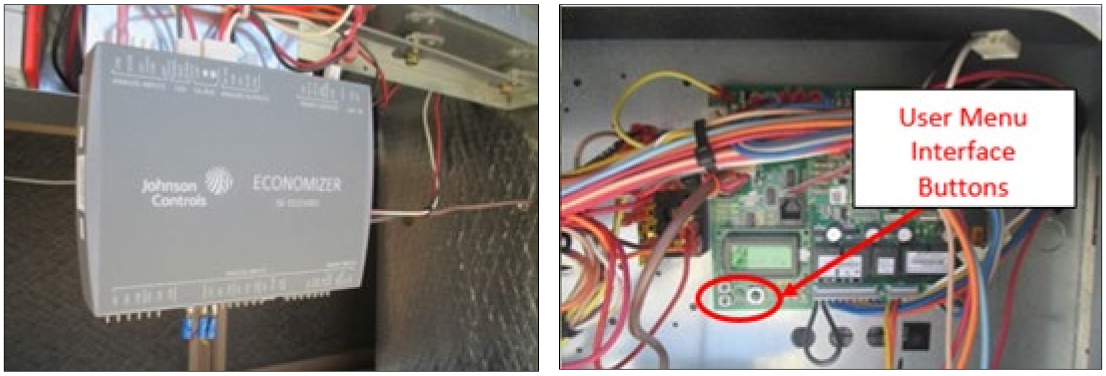


FIGURE 16: TYPICAL JOHNSON CONTROLS CONFIGURATION – ECONOMIZER CONTROLLER (LEFT) AND RTU CONTROL BOARD (RIGHT)

The Honeywell Jade has its LCD screen built into the controller. The display menu is limited to RTU heating and cooling operation. Like the ECO, it is the bridge between the RTU's control board and the damper actuator.

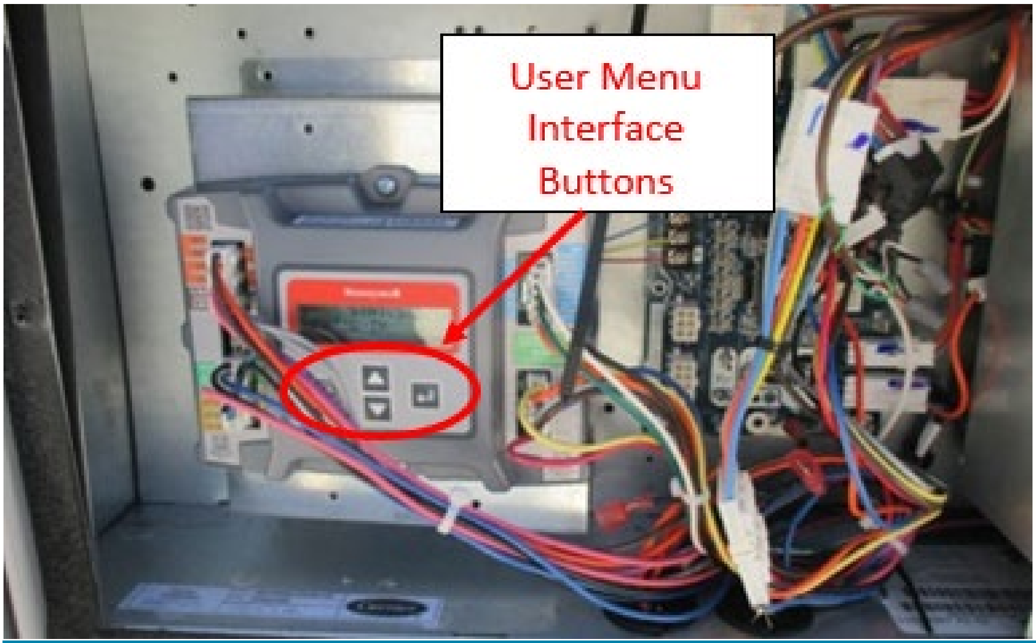


FIGURE 17: TYPICAL HONEYWELL JADE CONTROLLER INTEGRATED INTO ADJACENT RTU CONTROL BOARD

BMS Integrated Controllers: These are general HVAC controllers. They control all RTU functions: scheduling, heating/cooling, alarming ***and economizing***. However, unlike stand-alone controllers, BMS integrated controllers must be custom programmed for each unit.

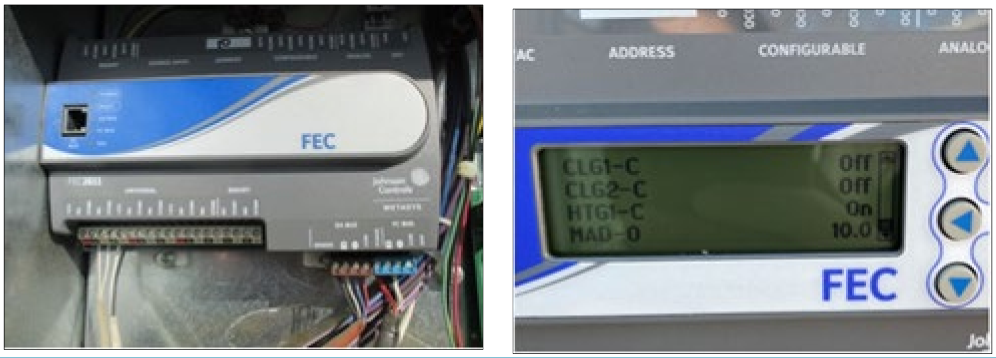


FIGURE 18: TYPICAL JOHNSON CONTROLS METASYS BMS CONTROLLER – NON-DISPLAY (LEFT) & DISPLAY (RIGHT) IN HEATING MODE, DAMPER AT MIN 10% OPEN POSITION

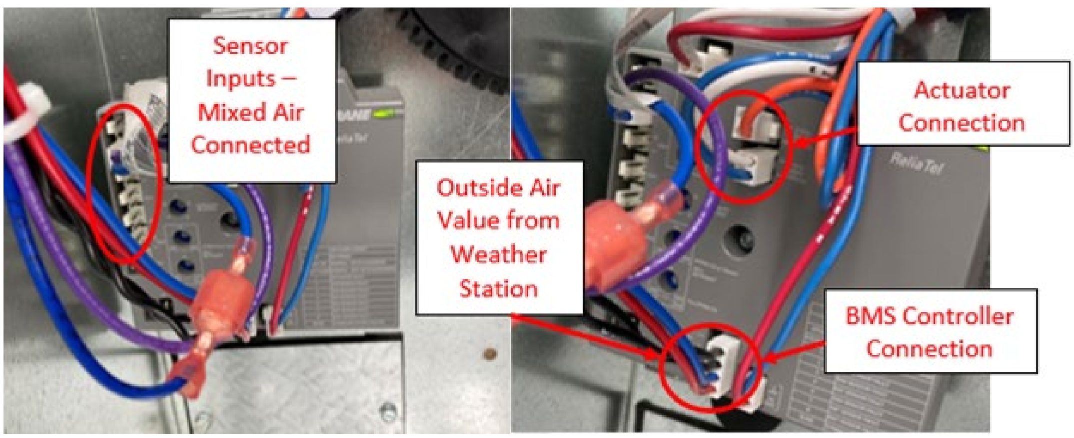


FIGURE 19: TRANE RELIATEL CONFIGURATION – MIXED AIR SENSOR CONNECTED & ACTUATOR AND BMS CONTROLLER

The Trane ReliaTel receives outside and mixed air readings from the temperature sensors, which are then relayed to the controller's via MSTP connection. The economizer logic is done at the controller, which then sends a damper actuator signal back to the ReliaTel.

Figure 19 displays a typical configuration for BMS systems, where the outside air temperature sensor is not directly connected to the ReliaTel, but rather the outside air value is brought in through the BMS connection from a global sensor.

FINDINGS: ECONOMIZER CONTROL CONFIGURATIONS

This section summarizes the economizer controller programming checks. The Study Team based the test on the Title 24, 2019 NRCA-MCH-05-A Air Economizer Controls Acceptance form. This portion of the test involved programming checks, sensor calibration and placement checks, and functional testing to determine whether the unit could maintain minimum damper position, 100% open position and damper modulation in between.

Overall, the investigation found most economizers did not pass their programming or installation checks, which prevented dampers from meeting their basic performance goals. The Study Team found the following issues with high frequency:

- High-limit settings did not comply to Title 24 requirements.
- Mixed air sensors were not installed, which prevented dampers from modulating properly

Some sites had a combination of the above two issues. In total, these issues caused dampers to be at their minimum position and the compressor engaged when outside air conditions were optimal for economizing. The following sections elaborate on the field assessment findings.

Controller Configuration and Settings

At each unit, the Study Team scrolled through the menu settings to find the high-limit cutoff setpoint. For all 16 stand-alone controllers examined, the investigation found the high-limit and mixed air setpoints were left at factory default settings. Table 17 shows the large differences between the outdoor air high-limit mandated by code and the default setpoint per controller. These sites would have failed their Title 24 acceptance test.

Table 17: Title 24 Code allowed vs. standalone high-limit default settings

Stand-alone Controller Model	No. of Units	Default Setting	CZ 03 & 04 Code Allowed	CZ 12 & 13 Code Allowed	Difference
Jade	7	63°F	73°F	75°F	10-12°F
ECO	9	55°F	73°F	75°F	18-20°F

At the default setting, Jade systems will not economize above 63°F outside air and ECO systems will not economize above 55°F. These settings are not suitable for economizing in California's climate. The Study Team's onsite inspections typically occurred in late morning or early afternoon when the ambient temperatures were well above the default high-limit setpoints. As a result, the Study Team found all 16 units at their minimum positions during initial visual inspections and had to manipulate the outside air sensor below 63°F or 55°F to force the damper to modulate to 100% open. Figure 20 shows the typical default outdoor air high-limit setpoints.

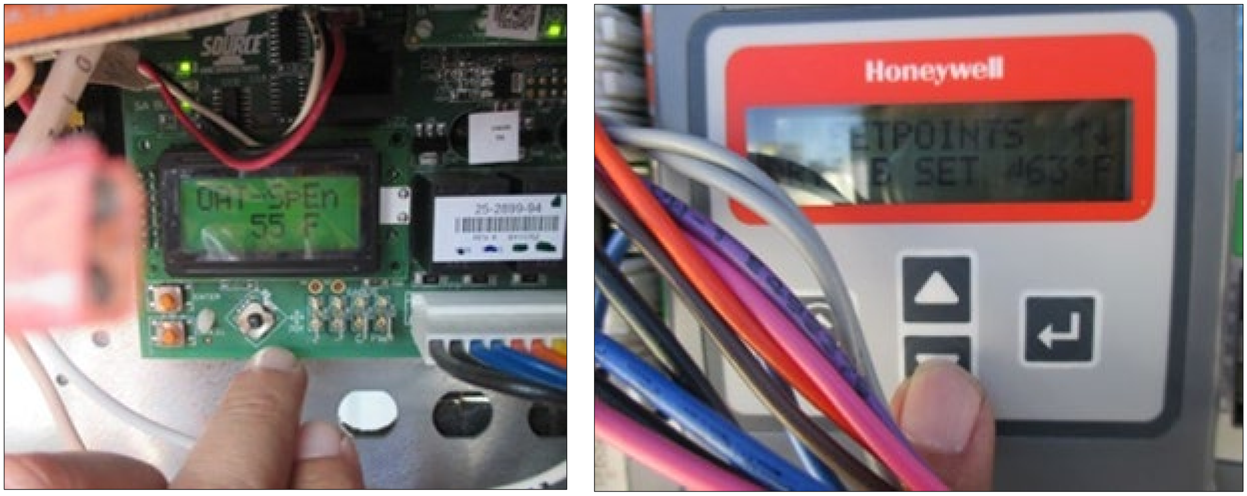


FIGURE 20: DEFAULT HIGH-LIMIT SETPOINTS – ECO AT 55°F (LEFT) & JADE AT 63°F (RIGHT)

For BMS integrated units, the high-limit setpoint needed to be custom programmed per unit. The Study found less than half of the units had their setpoint programmed and were capable of damper modulation. Table 18 shows:

- Only three units had high-limit setpoints that were within a reasonable range (72, 72, and 68 °F respectively) of their Title 24 allowed setting.
- One unit had a sub-optimal setpoint at 60 °F.
- Two units did not have their high-limit setpoint programmed. The Study Team confirmed these units did not have any economizer logic. Therefore, no energy savings occurred for these units.
- Three units had disconnected actuators. Their dampers were failed closed and could not modulate. The team could not determine if any economizer logic was programmed but no energy savings occurred for these units with the as-found conditions.

TABLE 18: SITES WITH BMS

BMS Controllers	No. of BMS Units	Economizer Optimally Setup	Economizer Sub-optimal Setup	Economizer Logic not Setup	Economizer Logic Setup Undetermined
MetaSys	9	3 (33%)	1 (11%)	2 (22%)	3 (33%)

Overall, the Study findings indicate both stand-alone and BMS integrated controllers cut off a significant number of potential economizing hours within California climate zones. In addition, some BMS integrated units are not getting programmed for economizer operation.

CALIBRATION

The field assessment found no problems with sensor calibration. The Study Team found all economizer temperature sensor calibration, both outside and mixed, was reliable and accurate. The field measurements typically matched the controller reported values to within +/- 2°F. Overall, the investigation found the factory-provided sensor hardware properly calibrated and in good physical quality, which Figure 21 demonstrates, where the reported versus measured values are within 1°F of each other.

FIGURE 21: MIXED AIR SENSOR IN MIXED AIR PLENUM – FIELD AT 77.8°F (LEFT) VS. REPORTED AT 78.6°F(RIGHT)

Outside Air Sensor Installation and Placement

The field assessment found most outside air sensors connected to their controller and installed in an appropriate location. Figures 22 and 23 below illustrate common outside air sensor location placements. Figure 22 shows a typical ECO controller sensor installation. They are usually installed at the lower corner of the unit, through a drilled hole and exposed to the open air but shielded from direct sunlight or wind.

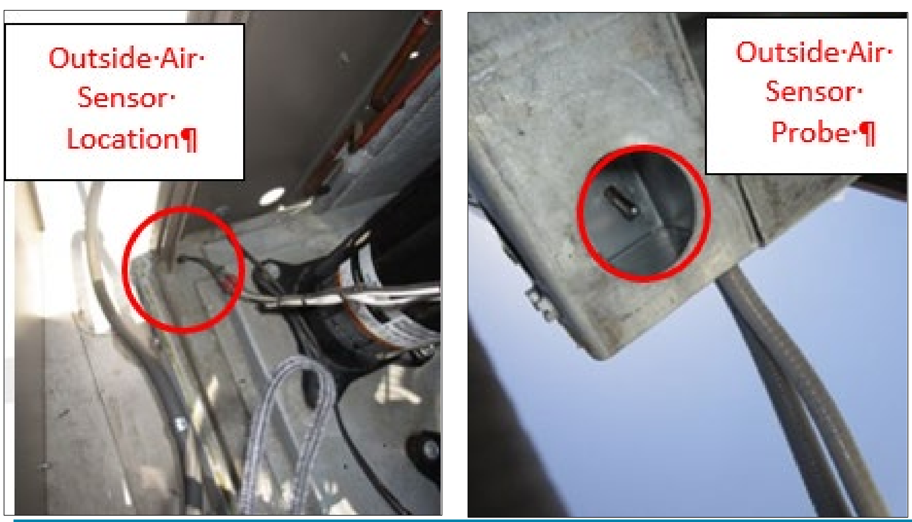


FIGURE 22: TYPICAL ECO OUTSIDE AIR SENSOR INSTALLATION – VIEW FROM TOP (LEFT) & VIEW FROM BOTTOM (RIGHT)

Figure 23 shows a typical Jade sensor installation. These are typically mounted to the unit near the outside air intake.

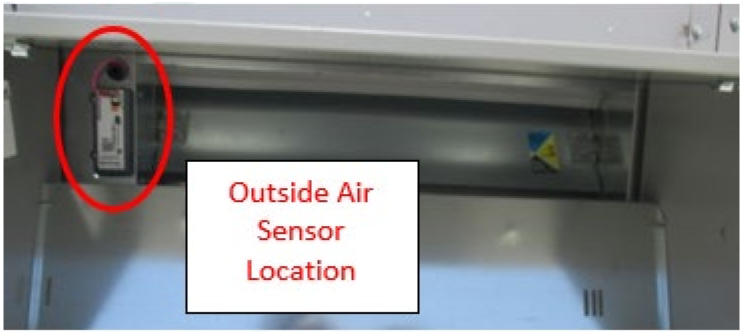


FIGURE 23: TYPICAL JADE OUTSIDE AIR INSTALLATION

Table 19 summarizes outside air sensor findings.

TABLE 19: OUTSIDE AIR SENSOR SUMMARY

Sensor Type	Expected Sensors	Installed and Connected to Controller	Installed in Good Location
Outside Air	25	23 (92%)	22 (88%)

Two units did not have their outside air sensors connected to their economizer controllers:

- At Site 6, there was no installation of either the sensor or its economizer controller within the RTU.
- At Site 11, the sensor was not connected to the controller. Figure 24 shows the outside air sensor installation problems at Site 11. The Study Team was able to find the sensor but found the link between the sensor and the control board was terminated. This site was a BMS integrated unit, but the economizer operation was not programmed.

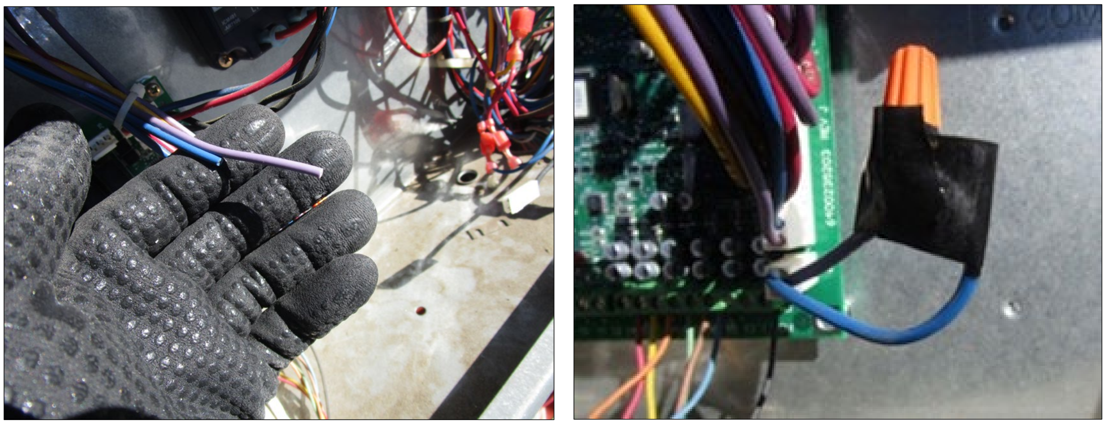


FIGURE 24: SITE 11 OUTSIDE AIR SENSOR INPUT TERMINATED AT RTU CONTROL BOARD

One additional unit had its outside air sensor connected, but it was not installed in a good location:

- At Site 13, while the sensor was connected to the controller, it was mounted in an exposed sunny area that caused a 5°F mismatch between field and reported conditions at the time of the Study team visit.

Mixed Air Sensor Installation and Placement

Unlike the outside air sensor, the mixed air sensor installation and placement was problematic. Just over half of the sensors were installed in the correct location. Table 20 summarizes the mixed air findings.

Table 20: Mixed air sensor summary

Sensor Type	Expected Sensors	Not Installed	Installed and Connected to Controller	Installed in Mixed Air Plenum	Installed Outside Mixed Air Plenum
Mixed Air	25	10 (40%)	15 (60%)	13 (52%)	2 (8%)

- Ten systems did not have their mixed sensor installed. As a result, the dampers were not able to hold any partial open position, for example 50% open. They could only operate either at their minimum or 100% open positions.
- Two additional systems had their mixed air sensor connected to their economizer controller, but the sensor was not installed in the mixed air plenum.

Figure 25 shows two different Jade economizer systems where the mixed air sensor was not installed.

Figure 25: Mixed air sensor not installed – Site 9 (left) and Site 4 (right)

- At Site 9, the Jade mixed air sensor was left uninstalled in its shipping package.
- At Site 4, the Jade mixed air temperature sensor was connected to the controller but installed in the same location as the outside air sensor.

At both sites, the Jade controller displayed the appropriate mixed air sensor error. These sites also demonstrate a problem with the Title 24 Mechanical Acceptance forms. The Study Team could not verify forms at Site 4; the office manager was not familiar with them when asked. It seems likely that acceptance was not enforced at Site 4. For Site 9, the MCH-05-

Outdoor Economizer form was provided by the installer/maintenance personnel and was "passed". However, since the mixed air sensors were not installed, the units should have instead failed.

FINDINGS: MINIMUM OUTDOOR AIR CONTROL CONFIGURATION

This section describes the damper and minimum ventilation findings. The Study expected all units to comply with Title 24 minimum ventilation requirements and have their damper at a minimum, open position when in heating and ventilation modes and when the outside air temperature was above the high-limit setpoint in cooling mode. The minimum open position is typically between 10 to 20% open, based on previous experience with economizer systems and Title 24 outside air calculations within the compliance forms.

Instead, the Study Team found a significant number of units with their dampers closed during heating, ventilation, and cooling modes, rather than the expected 10-20% open range. Table 21 summarizes the damper position findings.

TABLE 21: MINIMUM DAMPER POSITION BALANCING SUMMARY

No. of Units	Dampers Provided Fresh Air			Damper Closed Due To	
	Economizer Programmed with Open Minimum	Economizer Not Programmed with Open Minimum	Disconnected Equipment / Fixed Open	Disconnected Equipment / Failed Closed	Minimum Position at 0%
26	11 (42%)	1 (4%)	2 (8%)	4 (15%)	8 (31%)

Of the 26 units, 11 appeared to be properly balanced and had an appropriate minimum open position. These dampers held a partial open position and could modulate from minimum to 100% open.

Figure 26 shows Site 15 as a typical example of a unit meeting Title 24 minimum ventilation requirements. As expected, the damper blades were slightly open, the corresponding menu display showed the minimum position programmed at 15% open, and since the outside air temperature was above the high-limit setpoint, the compressor was on in cooling mode.

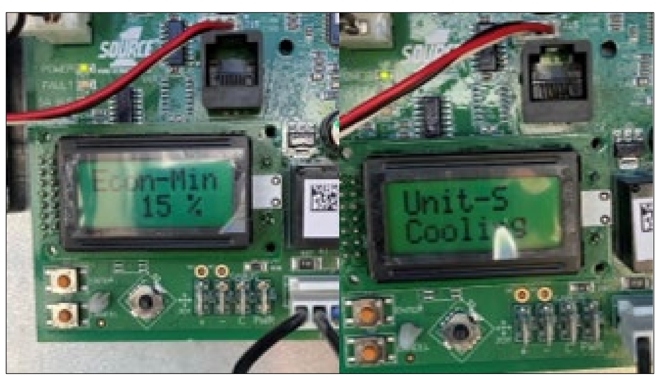


FIGURE 26: DAMPER AT MINIMUM POSITION (15%)

One unit had a minimum open position but did not operate its dampers with a dry-bulb economizer logic. Rather, the damper position was a function of fan speed – damper was at minimum position at low fan speed and 100% open at high fan speed.

Two units had disconnected actuators that caused the dampers to be fixed in the open position. They could not modulate but did provide the system some fresh air during operation. It was unclear if the amount of fresh air met Title 24 minimum ventilation requirements.

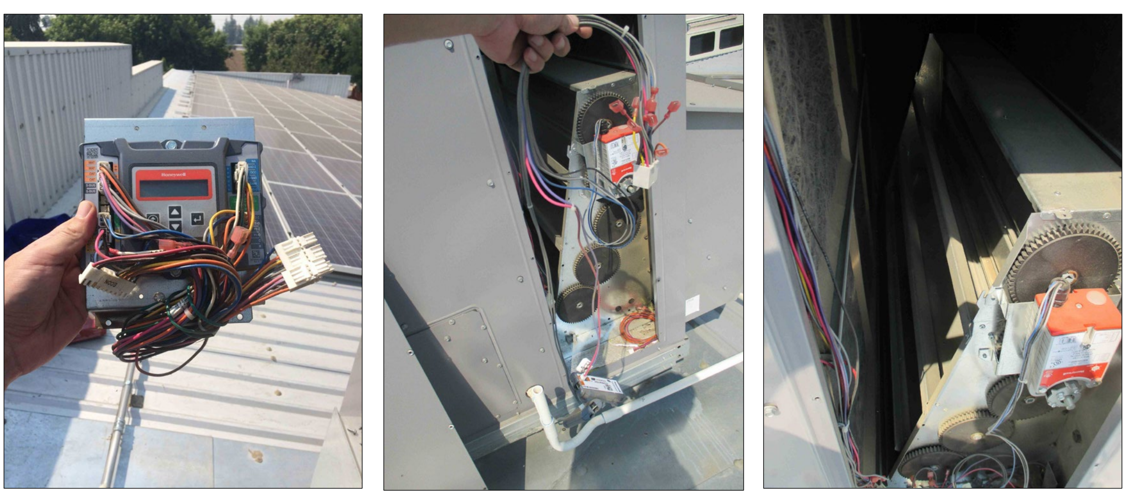
The remaining 12 units had their dampers (either failed closed or programmed in a minimum position of 0%) rather than in an open position, which means that return air is reconditioned and recycled back into the zone with only damper leakage providing ventilation air. According to 2016 ASHRAE 90.1, Section 6.4.3.4.3 - Damper Leakage, dampers "shall have a maximum damper leakage rate of 10 cfm per square foot". For these 12 units, while it is expected that closed dampers will have some leakage, the leakage is insufficient to meet minimum ventilation requirements.

The dampers seemed to be fixed in the closed position for one of the following two reasons:

1. **Physical failure.** Four units had disconnected actuators and/or controllers. These units were not physically capable of modulation and their dampers "failed closed"; or
2. **Programming failure.** For eight units, the damper minimum setting programming was 0% open instead of the expected design for 10-20% open. As a result, while the dampers were physically capable of modulation, they were closed during the site visit.

Figure 27 depicts the physical failure at Site 6. The RTU was designed and ordered for economizer operation but was never setup by the installing technician. The owners were unaware of the deficiency, but the occupants complained of stuffy air and odors from adjacent offices during lunch, indicating lack of ventilation.

In Figure 27, the left image shows the as-found conditions where the Jade Controller was never installed, nor were its sensors and actuator connected. The Study Team was able to pull out the economizer system from the unit. The middle image shows the disconnected



actuator and sensors. The right image shows the outside air damper blades completely shut. Without any controls to the damper, the default position was failed closed.

FIGURE 27: JADE CONTROLLER DISCONNECTED (LEFT), SENSORS NOT INSTALLED TO CONTROLLER OR ACTUATOR (CENTER), OUTSIDE AIR DAMPER AS FOUND CONDITION – FAILED CLOSED (RIGHT)

Figure 28 illustrates the minimum position programming failure found at Site 9. The unit was in operation and the economizer controller was installed and wired to the RTU's primary control board. During inspection, the outside air temperature was above the high-limit setpoint and unit was in cooling mode. However, instead of a minimum open position, the outside air damper was closed and return damper was fully open. The configuration at all three Site 9 units was this way.

FIGURE 28: OUTSIDE AIR DAMPER EXTERIOR (LEFT), CLOSED OUTSIDE DAMPER TOP, OPEN RETURN DAMPER BOTTOM (CENTER), ENERGIZED JADE ECONOMIZER CONTROLLER (RIGHT)

FINDINGS: ENERGY CODE COMPLIANCE

FAULT DIAGNOSTIC DETECTION SUMMARY

The Study based FDD compliance checks on the 2019 Title 24 acceptance tests: MCH-12 – FDDs for Package Direct Expansion Units. An important question for the Study was whether current FDD features uncover poor system set-up, leading to resolution. Per Title 24, Section 120.2 - Required Controls for Space-Conditioning System, Section (i), Economizer Fault Detection Diagnostic, in order to help determine current operation, economizer FDDs must satisfy the following three criteria:

- status information,
- faults information, and
- reporting.

The MCH-12 acceptance test incorporates these criteria, described further below:

- **System Status.** Ability to display current mode i.e., economizing, compressor stage, heating stage,
- **System Faults.** Ability for the system to display alarms i.e., sensor error, inconsistent economizer operation, damper failure, and excess outdoor air,
- **Reporting.** Per Title 24, Section 120.2(i)6, faults must be reported in one of the following ways:
  - Reported to an Energy Management Control System regularly monitored by facility personnel.
  - Annunciated locally on one or more zone thermostats, or a device within five (5) feet of zone thermostat(s), clearly visible, at eye level, and meeting the following requirements:
    - On the thermostat, device, or an adjacent written sign, display instructions to contact appropriate Building personnel or an HVAC technician; and
    - In buildings with multiple tenants, the annunciation shall either be within property management offices or in a common space accessible by the property or building manager.
    - Reported to a fault management application which automatically provides notification of the fault to remote HVAC service provider.

The findings indicated economizer controllers met the system status and fault requirements but typically did not comply with the reporting requirements.

All stand-alone controllers met the system status and faults requirements. The Jade and ECO controllers come with factory-provided status and alarms that can be found by scrolling through the controller menu options, which Figure 29 and Figure 30 show.

FIGURE 29: ECO (LEFT) AND JADE (RIGHT) CONTROLLERS DISPLAYING ECONOMIZER STATUS. BOTH SHOW NO ECONOMIZING AVAILABLE DUE TO OUTSIDE AIR TEMPERATURE ABOVE THEIR RESPECTIVE HIGH-LIMIT SETPOINTS.

FIGURE 30: ECO (LEFT) AND JADE (RIGHT) CONTROLLERS. BOTH DISPLAYING SENSOR ERROR ALARM FAULTS AS MIXED AIR SENSORS WERE NOT INSTALLED

The BMS systems typically displayed current system status through their graphic interface, which Figure 31 depicts, but typically did not have any alarms programmed, and thus had nothing to report to the BMS.

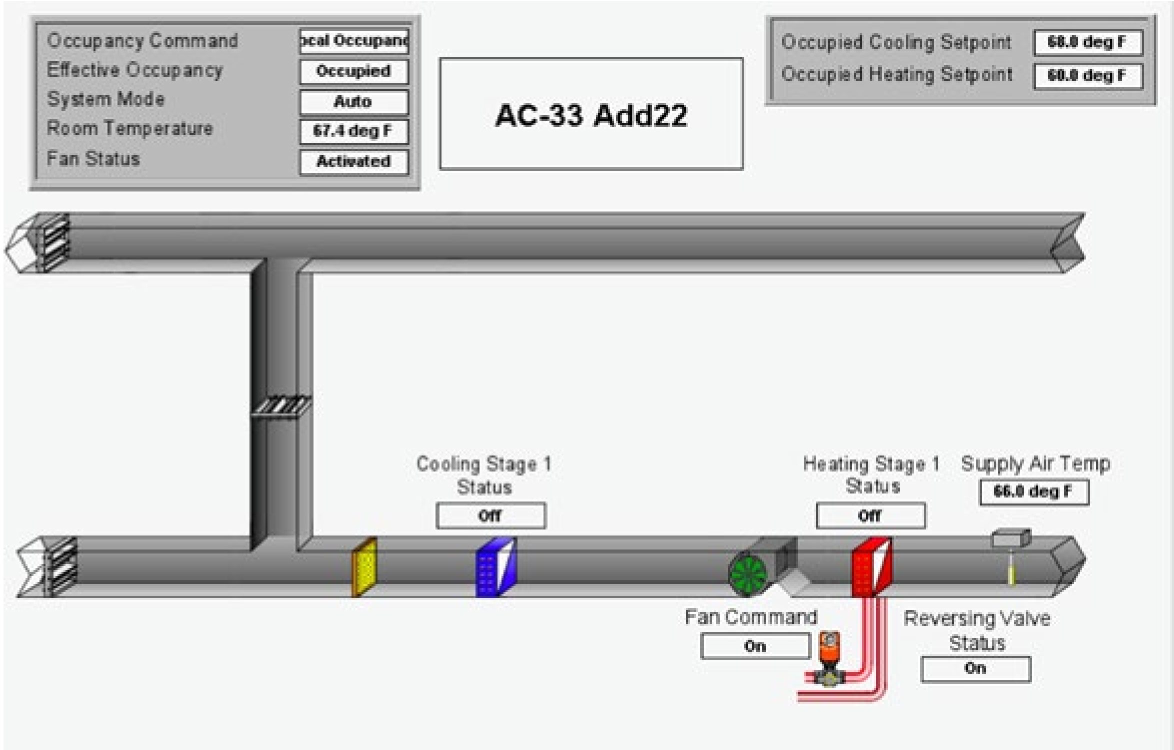


FIGURE 31: TYPICAL BMS GRAPHIC WITH COOLING, HEATING AND FAN STATUS

Table 22 summarizes each FDD compliance requirement, status, fault, and reporting, per site. The findings included:

- All sites but two met the system status requirement. Sites 3 and 6 did not have their controllers installed.
- All installed ECO and Jade economizer controllers met the system fault status requirement except Site 6 where a Jade controller was present but not installed.
- Five out of nine BMS integrated units did not have their alarms programmed and thus did not meet the system fault status requirement.
- Only 5 sites and less than half, 12, of the RTU units complied with the reporting requirements.
  - Site 7 met reporting requirement because their alarms were programmed and reported at the BMS.
  - Site 8 met the reporting requirement with a text notification to the third-party service provider.
  - Sites 9, 10 and 15 passed with an auxiliary alarm added to each thermostat.
- The same 5 sites and 12 units that passed the reporting requirement also passed the status and fault requirements, passing all the FDD requirements.

TABLE 22: FDD FINDINGS SUMMARY

Site	Control -ler	Provides System Status	FDD System Reports Fault	Met Reporting Reqs.	Reporting Method	Units per Site	Units Passed FDD Reqs.
2	ECO	Yes	Yes	No	None	2	0
3	None	No	No	No	None	1	0
4	Jade	Yes	Yes	No	None	1	0
5	ECO	Yes	Yes	No	None	2	0
6	Jade	No	No	No	None	1	0
7	ECO	Yes	Yes	Yes	Text to Service Provider	3	3
8	ReliaTel	Yes	Yes	Yes	Alarm to BMS	2	2
9	Jade	Yes	Yes	Yes	T-stat w/ auxiliary alarm	3	3
10	Jade	Yes	Yes	Yes	T-stat w/ auxiliary alarm	2	2
11	ReliaTel	Yes	No	Yes	To BMS Alarm not Programmed	1	0
12	ReliaTel	Yes	No	Yes	To BMS Alarm not Programmed	3	0
13	ReliaTel	Yes	No	Yes	To BMS Alarm not Programmed	1	0
14	ReliaTel	Yes	No	Yes	To BMS Alarm not Programmed	2	0
15	ECO	Yes	Yes	Yes	T-stat w/ auxiliary alarm	2	2
					Total	**26**	**12**

NON-ALARM COMPLIANT THERMOSTATS AND SUPPLEMENTAL DISPLAYS

The primary reason for FDD failure is that thermostats did not comply with the "annunciated locally on one or more zone thermostats, or a device within five (5) feet of zone thermostat(s)" requirement.

Figure 32 shows two typical, as-found thermostat conditions. They display room temperature and active mode (cooling, heating, or fan) but are not capable of displaying alarms. Both sites had active FDD alarms at the economizer controller due to missing sensors, but no alarms were annunciated at the zone level per code requirements. As a result, occupants were unaware that the units were in active alarm.

FIGURE 32: TYPICAL THERMOSTATS – SITE 2 (LEFT) AND SITE 4 (RIGHT). NO ALARMS DISPLAYED DESPITE ALARM CONDITIONS.

A common compliance approach found at sites with non-compliant thermostats was an auxiliary alarm sensor added to supplement the thermostat. This approach complied to the annunciated to the "device withing five feet of the thermostat" clause. Figure 33 shows four thermostats and four corresponding supplemental alarm devices found at Site 9. All four alarms were found 'active' as indicated by their green display light. Site 9 had mixed air sensor alarms at the economizer controllers. However, it was unclear if the active alarms at zone level corresponded to same mixed air sensor alarm or other condition such as the 'service filter' alarm that was also found active. Furthermore, even though the auxiliary alarm sensor approach made this site compliant with FDD requirements, it did not appear to be effective at this site because the alarms had been active for quite some time.

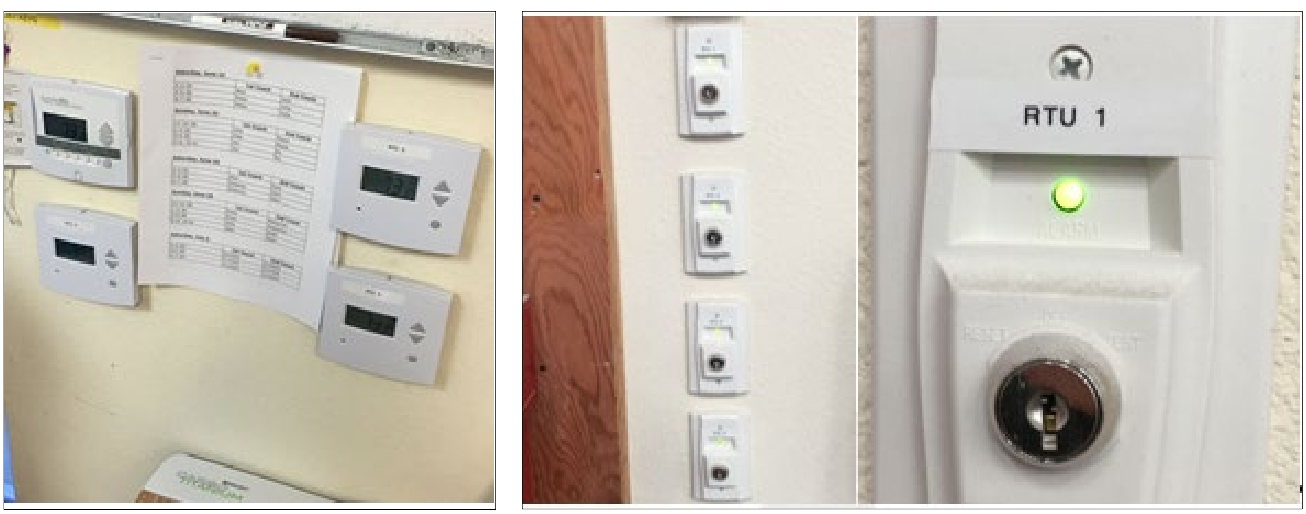


FIGURE 33: FOUR THERMOSTATS (LEFT) WITH FOUR CORRESPONDING SUPPLEMENTAL ALARM DISPLAYS (MIDDLE) AND ALARM IN "ACTIVE" MODE (RIGHT) AT SITE 9

Figure 34 shows a similar configuration at Site 15, where an auxiliary alarm was added to comply with reporting requirement. The team created an alarm condition by unplugging the outside air sensor and observed the alarm turn active as indicated by red indicator light.

FIGURE 34: RTU FDD TRIGGERED (LEFT), ALARM AT ZONE LEVEL ADJACENT T-STAT (RIGHT)

The Study Team also noted none of the sites complied with the Title 24, Section 120.2(i)6 reporting requirement, under the annunciated locally at the thermostat requirement's first sub-bullet, to have "on the thermostat, device, or an adjacent written sign, display instructions to contact appropriate building personnel or an HVAC technician." None of the sites, even the ones with supplemental alarms, had any signage visible.

Overall, the Study found the following reasons for poor FDD efficacy:

- Typical thermostat hardware did not come with alarm status options that comply with Title 24 reporting requirements.
- To meet Title 24 reporting, the installing contractor must install supplemental hardware and perform additional setup and integration.
- Contact information for the HVAC service provider and/or instructions on what to do in the event of an active alarm were not found at any sites. Occupants were unaware when units were in alarm.
- Even with supplemental alarms, at the zone level, it was unclear what the specific alarm condition is since the only indicator of a problem is an active light.
- The only way to determine the specific cause of an alarm was to access the economizer controller, within the unit, on the roof, and scroll through the menu options.

For FDDs to be effective as intended, users must be trained to call the HVAC service provider when an alarm is active. Maintenance personnel must then know how to identify active alarms at the economizer controller menu. Then maintenance personnel must correct the error and manually clear the alarm. The findings on FDD efficacy indicate that installation and setup errors that are not addressed during installation will persist as long as the RTU appears to function.

FINDINGS: ACCEPTANCE TESTS

Research question 4 asked:

> ***Are current acceptance tests uncovering poorly set up of systems? What gaps and opportunities for improvement exist in the acceptance test enforcement procedure related to physical and procedural compliance?***

As a part of the Study, the team requested that participants share relevant design documents and compliance documentation (including Title 24 documents). Mechanical schedules; Title 24 compliance forms; Title 24 mechanical acceptance forms; or test, adjustment, and balance reports (TAB) help the team determine whether design and testing of the unit complied with economizer requirements.

Very few sites provided these documents. Most site contacts did not know where these documents were kept or if they even existed. This dearth of forms and the operational faults and programming errors observed in the Study led the Study Team to conclude that in most cases building inspectors had not enforced acceptance testing requirements. Of the 15 sites, only three had any information regarding mechanical acceptance forms:

> Site 9: The installing/regular maintenance contractor filled out the 2013 MCH-05 Air Economizer Controls form with a passing result. Given the mixed air sensors were not installed at this site, the result should have been a failure. If the local authority having jurisdiction (AHJ) examined the forms, they did not perform any due diligence.
>
> Site 10: This site was a recent new construction. The Study Team asked the general contractor whether the local AHJ was enforcing the acceptance requirement and he responded they were not. No acceptance tests were conducted or planned.
>
> Site 15: This site was also a recent new construction. The installing contractor had filled out the 2019 MCH-05 form with a passing result; however, the high-limit setpoint were left at 55°F default, which should have resulted in a failure. It was also unclear if the local AHJ was enforcing acceptance testing. The installers had to produce the forms as part of their contractual obligations to ownership.

The remaining sites were pre-2019 code and most would have failed their 2013 and 2016 acceptance tests had the inspections been done properly. These Pre-2019 forms, however, did not adequately specify code requirements; this ambiguity could have contributed to the overlooked failures. Below are two such examples:

> The 2013 and 2016 MCH-05 - *Air Economizer Controls* forms were insufficient to identify problems with the low, factory-default high-limit settings. The tests only required a single check box to confirm that the "Economizer high limit shutoff control complies with the Table 140.4-E found in the Building Energy Efficiency Standards Section 140.4(e)3." This forced the acceptance tester to independently reference Table 140.4-B, which would be inconvenient during a typical site visit.

> The 2016 MCH-12 *FDD Packaged Direct Expansion Units* form only required general 'Yes or No' checks such as "Fault Detection and Diagnostics hardware is installed on the unit" or that "the FDD system reports a fault". The form did not list how or where the fault was reported. This allowed systems to pass since faults reported at the controller technically met the form requirement. However, these systems should have failed, since faults were not reported to an EMS, zone thermostats or fault management application, as required by Title 24 code.

Updates to the 2019 MCH-05 form include explicitly stating Table 140.4-E high-limit setpoints by climate zone on the form. Similarly, updates to the MCH-12 FDD Form from 2016 to 2019 code cycle include explicitly stating the required faults at the controller and fault reporting method. Acceptance tests using 2019 MCH-05 would have flagged the faults and errors present at the time of installation observed at the Study sites. While the Study Team did not identify any remaining gaps in the current acceptance testing forms or procedures, our findings indicate that few sites experienced enforcement of Title 24 requirements by their local jurisdiction and furthermore on the rare occasion when the forms were executed, they were done by the installing contractor, not an independent third-party tester. This resulted in setup errors not getting caught possibly because the installers were unaware of Title 24 economizer requirements.

It should be noted that acceptance testing requires several hours of on-site work. Thus, particularly for installations of small quantities of smaller capacity RTU/economizers where the cost of the acceptance testing may be high relative to the value of the energy savings at risk, it is not surprising that proper acceptance testing may not be happening in jurisdictions that don't enforce acceptance testing requirements.

ENERGY MODELING AND IMPACT ANALYSIS FINDINGS

The Study Team developed building energy models and impact analyses for the average non-residential building to estimate the difference in energy use in typical commercial buildings to answer research question 3:

> ***What are the energy savings implications of the observed underperformance of operational controls of economizers with respect to energy use, load shapes and system coincident peak?***

The Study used building energy modeling to estimate the typical impacts on energy use and operational costs based on the findings of the site visits. The Study used prototype energy models of nonresidential buildings, selecting a set of buildings where RTU/economizers are typically used. The energy model represented Study fault and error findings as parameters (referred to as "fault parameters"). The Study simulated fault parameters to assess the impact of each alone and in combinations. The Study then combined annual energy results based on the frequency of observed faults from the site visits to estimate the average change in energy for each prototype building by climate zone. The Study then further scaled energy results to estimate a whole market level impact by extrapolating the frequency of faults from the site visit findings using a past field investigation of RTU/economizers in California with a statistically representative sample size.

KEY FINDINGS

1. The Study estimated that on average the cooling energy use of RTU/economizer units in new construction applications would operate at a 47% increase in HVAC electrical energy use in single speed RTUs and 30% in two-speed RTUs.
2. Of the three fault parameters evaluated, the Study found the largest change in HVAC energy use was attributable to the RTU/economizer outdoor air high-limit temperature setpoint, which governs when the economizer is on or off.
3. Of the three fault parameters evaluated, the Study found the largest change in code compliance was the RTU/economizer minimum outdoor air damper position being above ventilation minimum, which is also the metric that represents the largest life cycle cost of energy. The Study found the reduction in code compliance for buildings with this problem was:
    a. -4.6% on average for new buildings with RTU/economizers that maintain 150% of ventilation at minimum.
    b. -17.9% on average for new buildings with RTU/economizers that maintain 200% of ventilation at minimum.
4. Between the two speed control options evaluated for RTU/economizers, the Study found systems with two-speed fans and two compressors were more resilient, more closely maintaining the estimated energy use with the presence of operational faults. While operational faults still increased energy use, the two-speed systems' performance impact was less than that seen in single speed systems for each operational fault.

ENERGY MODELING PARAMETERS

The Study used energy modeling and analysis to represent the observed operational faults and programming errors in RTU/economizer systems. The Study Team aggregated Study findings into specific fault parameters, economizer control configurations covering functionality and outdoor setpoints, temperature sensor configurations, and minimum outdoor air control configurations.

For each parameter, the Study Team identified specific scenarios to capture the impacts in a typical building. For fault parameters, the Study based scenarios on the field assessment to characterize site configuration. The Study developed scenarios using rounded off numbers and step changes in the magnitude of fault parameters. Table 23 shows the scenarios evaluated for each fault parameter.

TABLE 23: ENERGY MODELING FAULT PARAMETER SCENARIOS USED IN ANALYSIS

Fault Parameters	Scenario	Scenario Description
Economizer Control Parameter	1	Economizer Enabled
	2	Economizer Disabled
	3	Upper Limit Dry Bulb Reduced by 5°F
	4	Upper Limit Dry Bulb Reduced by 10°F

	5	Upper Limit Dry Bulb Reduced by 15°F
Mixed Air Parameter	1	Working in proper location
	2	Improper Location, equivalent bias +2°F
	3	Improper Location, equivalent bias +3°F
Minimum Outside Air Parameter	1	Working per Code Requirements
	2	Minimum fixed at +50% above ventilation
	3	Minimum fixed at +100% above ventilation

The Study Team selected economizer upper limit outdoor air control setpoint settings in 5°F increment reductions up to a 15°F in total. The Study Team estimated mixed air control by adjusting the mixed air sensor reading by 2°F and 3°F as representative scenarios. For the analysis, the Study Team selected an increase in degrees to evaluate the impact of this sensor placement on cooling energy, representing a signal higher than the actual mixed air condition. A positive bias is modeled; when misplaced, the mixed air sensor was always installed in a spot where readings would be higher than the correct location during cooling. The Study Team selected 2°F and 3°F as the scenarios for the analysis to represent a reasonable seasonal average offset. Some sites located the sensor completely outside the unit, which would be equivalent to a much higher temperature bias, perhaps 8°F to 10°F, on hot days. For the minimum outside air control, the simulation only considered field findings of sites configured correctly or with excessive outside air when at minimum damper position to ensure all options being simulated maintained building ventilation minimum standards.

The Study Team then evaluated energy use per building floor area to understand the impact of the identified fault parameters in each building type. The Study assigned each thermal zone in each prototype building a dedicated single-zone RTU/economizer system. This analysis did not use the resultant size of the thermal capacities of each RTU as an indication for when it should or should not include an economizer, which is how Title 24 compliance software evaluates building energy models. Rather, the energy analysis used the prototype buildings to primarily provide thermal load shapes and evaluated loads and energy flows per building area (per square foot of building area). This methodology allowed the energy modeling to be simplified to evaluate only buildings where economizers would have been required.

Findings: Economizer Control Configuration Fault Impacts

The outdoor air dry-bulb temperature directs an economizer's primary control signal. An economizer enables when outdoor air temperatures are at or below a set threshold depending on the building location. In Oakland (CZ03), this limit should be 75°F while the limit should be 73°F in San Jose (CZ04). The simulated scenarios reduced this upper limit in three steps by increments of 5°F from the limit set in Title 24 energy standard today. A final fourth step simulated the economizer completely disabled.

In all climate zones, the greatest change in cooling energy occurred when economizer upper limit lockout controls were limited. The two scenarios simulated were -10°F and -15°F below the upper limit dry bulb. As an example, in CZ03, this limited operations to 65°F and 60°F. Several field assessment sites with this fault parameter were at this level of offset or beyond, with sites reporting 55°F lockout limits in some cases. Two-speed RTUs show a lower increase in cooling energy, suggesting this increased functionality can be used to minimize faults in control configurations.

Figure 35 shows the result for each building and two types of RTU/economizer units, one with a single speed and one with two speeds, in CZ03 and CZ12. CZ03 shows the greatest relative change to cooling energy, with the upper limit by -15°F increases cooling energy by 193% in single-speed RTUs and 40% in two-speed RTUs.[19]

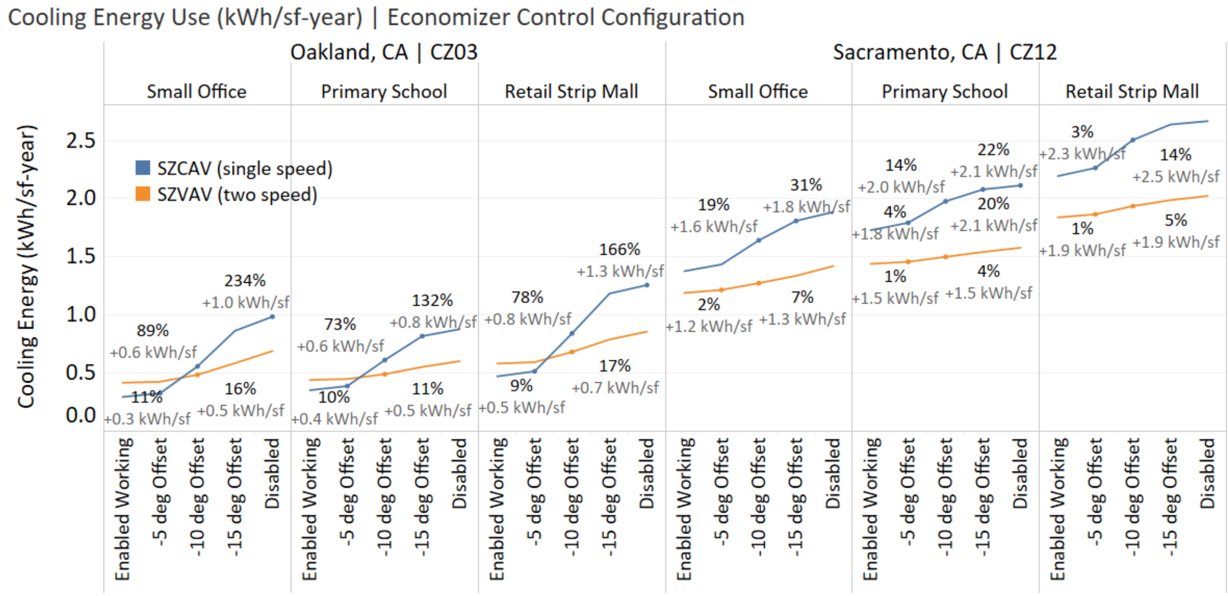


FIGURE 35: ENERGY MODELING RESULTS FOR ECONOMIZER CONTROL CONFIGURATION FAULT OF TOTAL COOLING ENERGY CONSUMPTION (KWH/SF-YEAR), CZ03 AND CZ12

Figure 36 shows the resulting change in energy code compliance for each building (new construction), temperature offset, and RTU/economizer type in two climate zones. As an example, small offices in a mild climate, like CZ03, with single speed RTUs show a code compliance reduction of 7.5% at -15°F offset.[20]

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[19] Some of the data labels for annual cooling energy per square foot and percent increase above the "enabled working" scenario for each of scenarios are excluded due to space constraints. Data labels are shown only at -10 degree offset and "disabled" status for single-speed and -5 and -15 degree offset for two-speed units.

[20] A reduction in compliance value means that the building is expected to have an increased energy cost.

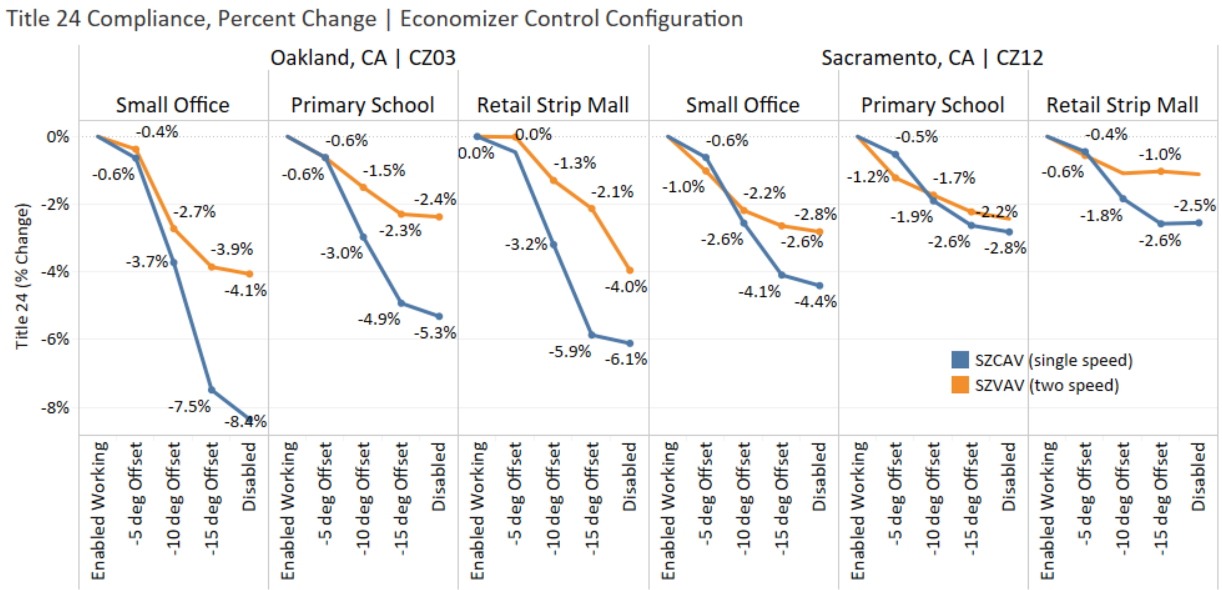

FIGURE 36: ENERGY MODELING RESULTS FOR ECONOMIZER CONTROL CONFIGURATION FAULT IN CHANGE IN CODE COMPLIANCE (% TDV), CZ03 AND CZ12

Adjusting this fault parameter resulted in a slight reduction in gas use in all cases as the economizer went from enabled to disabled; the reduction for the most sensitive building type in the most extreme climate zone was less than 0.01 therms/sf change in gas use based on the simulated energy models.

FINDINGS: MIXED AIR TEMPERATURE SENSOR FAULT IMPACT

The mixed air temperature represents the air temperature of return room air mixed with outdoor air. The analysis used the mixed air temperature to determine what stage of cooling the unit should be in and how to set the economizer dampers. The Study found the location of the mixed air temperature sensor was frequently incorrect, in most cases measuring the outdoor air temperature. To evaluate the potential energy impacts of this, the simulated energy model represented this installation error in two scenarios of increased bias, 2°F above the actual reading and 3°F in the reading itself. Figure 37 shows the results of the energy analysis below.

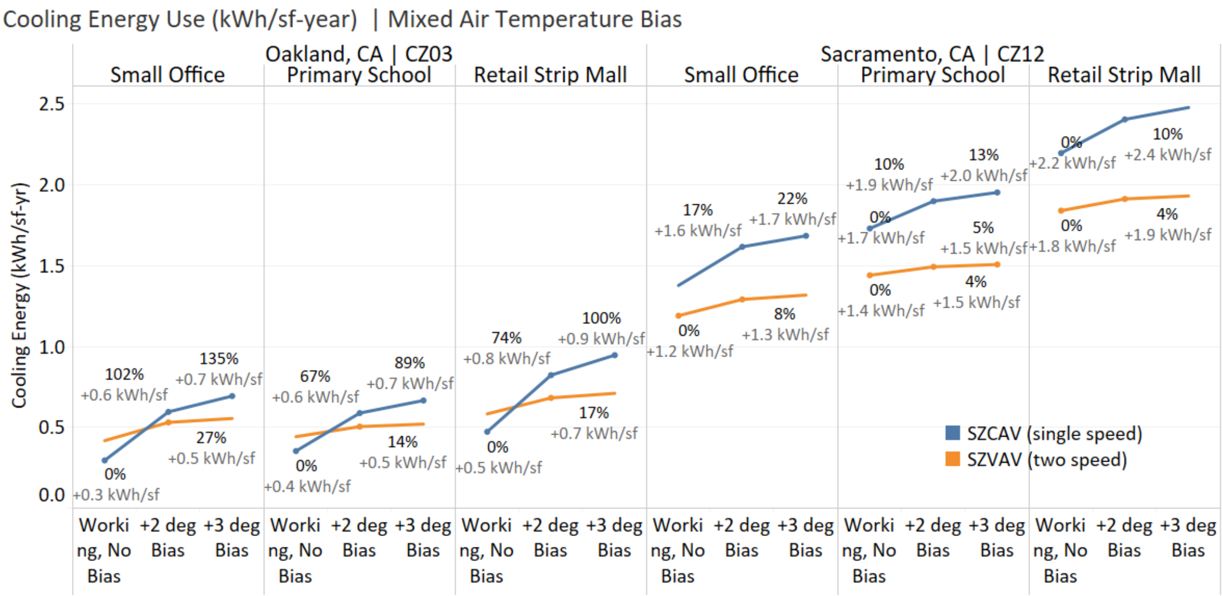

FIGURE 37: ENERGY MODELING RESULTS FOR MIXED AIR TEMPERATURE SENSOR FAULT OF TOTAL COOLING ENERGY CONSUMPTION (KWH/SF-YEAR)

In mild climates where a large portion of cooling is provided by economizing, the relative impact is quite high, with cooling energy increasing by 89% to 135% in single speed RTUs in the 3 degree bias scenario. In warmer climates, where cooling is only partially provided by economizing, the relative impact was lower, 13% to 22% increases for single speed RTUs, though the nominal cooling energy use overall increased by higher margins, between 1.7 and 2.4 kWh/sf-year compared to 0.7 to 0.9 kWh/sf-year. Figure 38 shows the same fault parameter impact on energy code compliance.

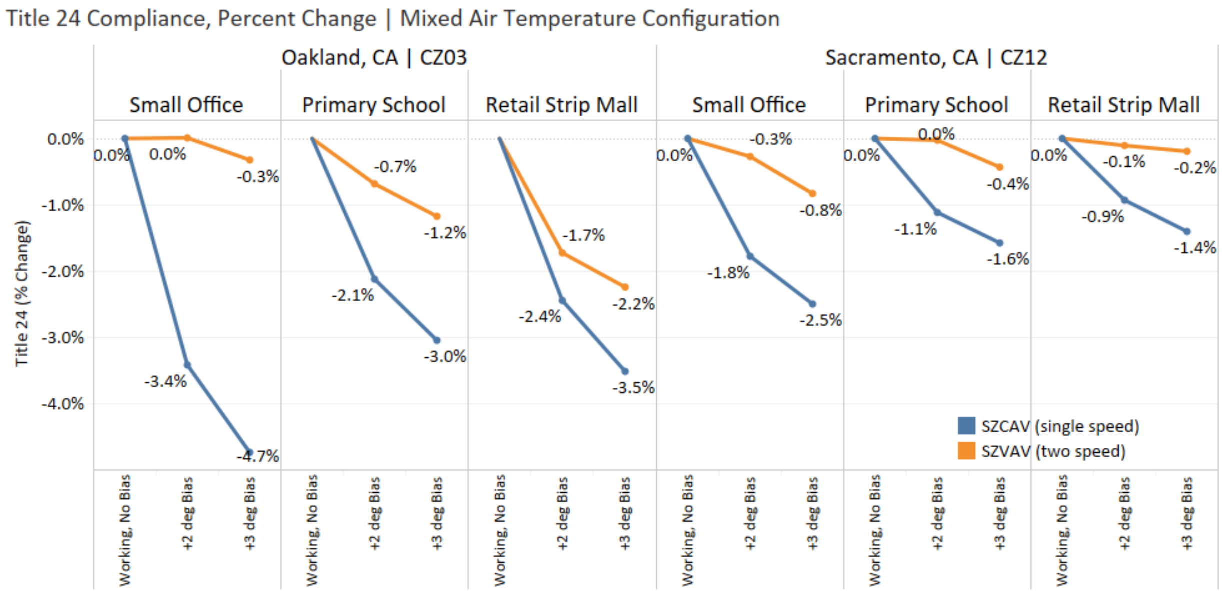

FIGURE 38: ENERGY MODELING RESULTS FOR MIXED AIR TEMPERATURE SENSOR BIAS FAULT IN CHANGE IN CODE COMPLIANCE (% TDV)

Figure 38 shows the impacts on code compliance of the mixed air temperature location in single and two-speed RTUs. In the retail strip mall building, a 3°F bias reduced the buildings margin of code compliance by -2.2% with a two-speed RTU and -3.5% with a single-speed RTU in Oakland, CA (CZ03). The figure shows similar but smaller relative impacts in the warmer climate, Sacramento, CA (CZ12).

FINDINGS: MINIMUM OUTDOOR AIR CONTROL FAULT IMPACT

The minimum outdoor air control fault parameter simulates an RTU/economizer that was restricted or set incorrectly for the minimum airflow the unit provided when not in economizer mode. The control fault could be either that dampers were fully closed or open higher than the ventilation minimum airflow when operating but not economizing. The energy analysis simulated two cases of airflow minimum setpoints maintaining higher than the required ventilation minimum airflow.

This minimum outdoor air control fault simulated the scenarios where the outdoor air damper was only able to turn down to a lower limit of 150% of the ventilation minimum and 200% of the ventilation minimum for the building. These two values were selected to simplify the analysis and to represent a reasonable lower limit based on how RTU/economizers are typically sized where the full airflow can often be 600% to 700% of ventilation requirement airflow. In balancing the lower limit for a modulating damper, depending on the application, the airflow limit may need to be between 15% and 30% of the full airflow. The damper position must be within a few degrees of the correct rotation to deliver the proper airflow. Thus, the airflow setting is prone to error if the damper modulation is not properly configured.

The modeling showed that these excessive minimum air flow limits most strongly impacted energy consumption in warmer climates, CZ12, 13 and 16. Figure 39 shows results for two climate zones by building type and RTU speed control. In Sacramento, CA (CZ12), the primary school energy model shows an increase in cooling energy of 0.1 kWh/sf to 0.3 kWh/sf-yr for single speed RTUs at the fault scenarios. In mild climates (CZ3, 4, 6), the analysis found a smaller change in cooling energy. In Oakland, CA (CZ03) the increase in cooling energy was 0.1 kWh/sf-yr in the most extreme case with primary schools and less than this in other building models.

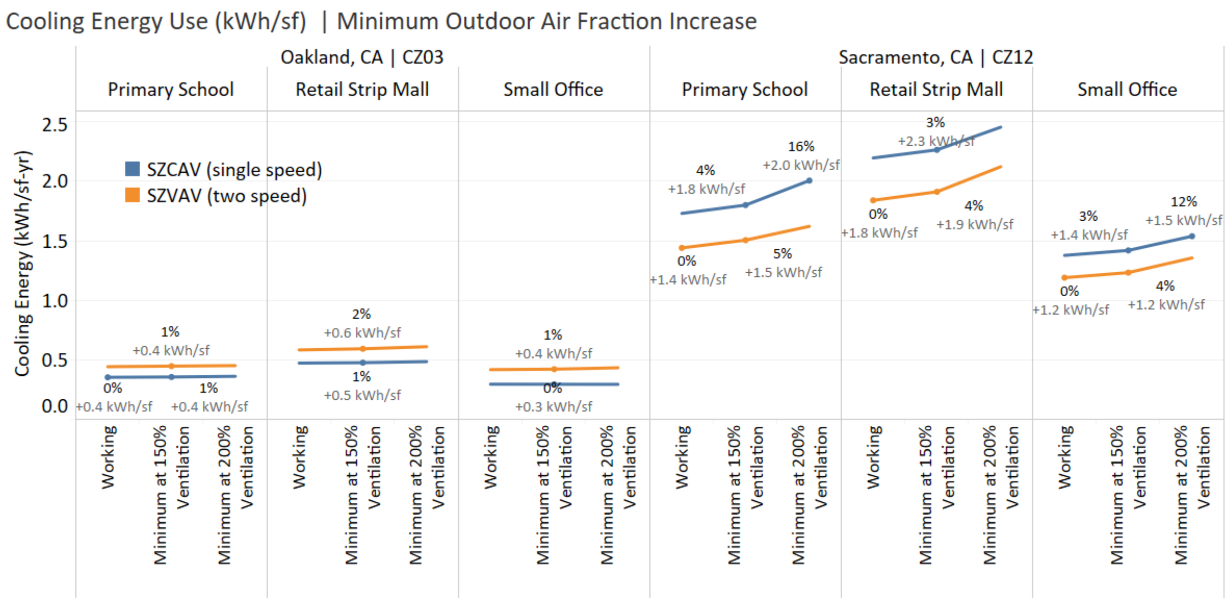

FIGURE 39: ENERGY MODELING RESULTS FOR MINIMUM OUTDOOR AIR FRACTION FAULT IN INCREMENTAL ELECTRICAL ENERGY (KWH/SF-YEAR)

Figure 39 shows that only warmer climates experienced a substantive change in cooling energy use. Figure 40 evaluates the same minimum outdoor air control faults for code compliance and utilizing the life-cycle-energy-cost metric TDV; each building and climate zone see substantial changes in the margin of percent savings, with all single speed RTU results showing -15% or lower and two-speed RTUs -20% or lower. The analysis shown in Figure 40 is for two-speed RTUs with control faults versus two-speed RTUs without control faults.

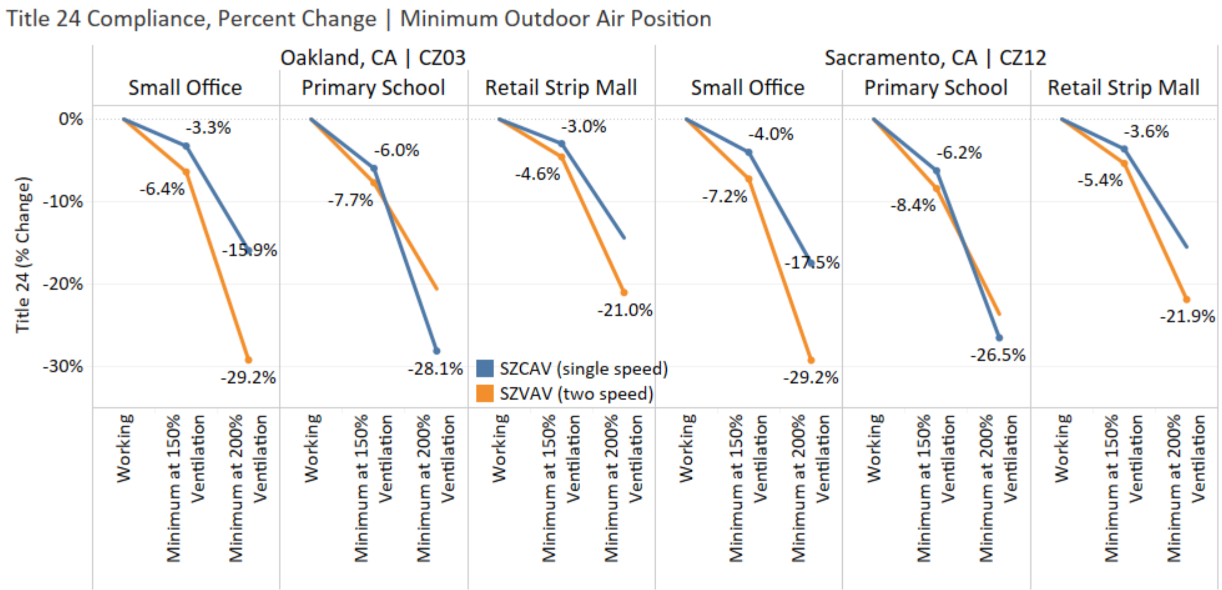

FIGURE 40: ENERGY MODELING RESULTS FOR MINIMUM OUTDOOR AIR FRACTION FAULT IN CHANGE IN CODE COMPLIANCE (% TDV)

The code compliance life cycle cost metric, TDV, weights hours of energy use more heavily during peak hours on the electrical grid than off peak hours. The analysis results indicate that the economizer control fault and the mixed air sensor bias cause relatively small changes in TDV as a percent of total energy since both of these faults tend to increase cooling energy during off peak hours. The higher minimum outdoor air fault results in an increase in cooling and heating energy during all times of the day, both on peak and off peak hours, resulting in largest change in TDV as a percentage of the three faults evaluated. Over the life cycle of these RTU/economizer units, those with problematic dampers and excess outdoor air will see the highest operating cost impacts of the three faults evaluated.

FINDINGS: COMBINED IMPACT OF RTU/ECONOMIZER FAULTS BASED ON FIELD SITES

While the results of the first step of the energy modeling analysis are useful for understanding the impact of each fault parameter, they only represent each fault individually. As noted in a previous section, the Study found that many RTU/economizers had multiple faults present and that some RTU/economizers had no faults. Because the Study objective was to estimate the average impact on performance for new RTU/economizers installed in California, the next step in the analysis was to assess the typical impact on operational energy use of a generic building with an RTU/economizer.

The second analysis step combined multiple simulated results based on the frequency of observations of each fault scenario in the Study. Across the 26 units, the Study found 16 unique combinations of fault scenarios, a frequency based on the number of observations of specific parameters during the Study. Table 24, Table 25 and Table 26 summarize the mapping of fault frequencies from the Study to frequency of fault scenarios.

TABLE 24: FREQUENCY OF ECONOMIZER FREE-COOLING CONTROL FAULT SCENARIOS BASED ON FIELD SITE OBSERVATIONS

Scenario	Economizer Control Parameter	Total Units	Number of Units	Percentage
1	Enabled Working	26	3	12%
2	Disabled	26	6	23%
3	-5 deg offset	26	0	0%
4	-10 deg offset	26	8	31%
5	-15 deg offset	26	9	35%

For the economizer control parameter, only 25 of the 26 units included an observation of the economizer control configuration. The analysis applied percentages to 4 of the 5 scenarios based on field findings (i.e., the Study did not apply percentages to scenario 1 because it was fully operational).

TABLE 25: FREQUENCY OF THE MINIMUM OUTSIDE AIR FRACTION FAULT SCENARIOS BASED ON FIELD SITE OBSERVATIONS

Scenario	Minimum Outside Air Parameter	Total Units	Number of Units	Percentage
1	Working	14	11	79%
2	Outside Air Minimum 150%	14	1	7%
3	Outside Air Minimum 200%	14	2	14%
n/a	Not simulated: Min to zero	n/a	8	n/a
n/a	Failed closed	n/a	4	n/a

For the minimum outside air parameter, 26 units had reported observations, though 4 of the units had failed closed and 8 additional units had minimum airflow positions of 0% open. Two of the units had higher than ventilation minimum airflow positions when in the minimum damper position. There were 11 units operating correctly. The analysis utilized only the units that maintained ventilation airflow (14 of 26) as the denominator of number of units evaluated. Sites where the overall reduced ventilation created a health hazard and would potentially result in less energy consumption were not included in the analysis total.

TABLE 26: FREQUENCY OF THE MIXED AIR TEMPERATURE READING FAULT SCENARIOS BASED ON FIELD SITE OBSERVATIONS

Scenarios	Mixed Air Parameter	Total Units	Number of Units	Percentage
1	Working, No bias	25	13	52%
2	+2 deg bias	25	6	24%
3	+3 deg bias	25	6	24%

The Study reported a mixed air temperature sensor parameter at 25 of the 26 units and included 13 units that operated as anticipated and 12 units that had problematic mixed air sensor installation. The Study Team represented these installation problems in the model as a bias in reading warmer temperatures than were present. The analysis allocated these 12 units equally between the two fault parameter scenarios (reading 2 and 3°F warmer than actual mixed air temperature) in the energy simulation.

The analysis simulated each combination of the three fault parameter scenarios in a parametric analysis and used the operational fault and programming error frequencies from the Study described in Table 24, Table 25, and Table 26 as the basis for how frequently each scenario occurred. The Study Team compared the weighted average performance resulting from the parametric analysis against a properly operating RTU/economizer.

This second step of the analysis shows an increase in RTU/economizer electrical energy use from increased cooling for the three building prototypes. Figure 41 and Figure 42 show results for single-speed RTUs and two-speed RTUs. RTU/economizers performance was most impacted in mild climates where more hours of economizing potential exist; the highest increase in energy use was in CZ06 (Torrance, CA). In Torrance, CA, the single speed RTU energy use would increase by 9% RTU/economizer electrical energy use, 0.5 kWh/sf-yr.

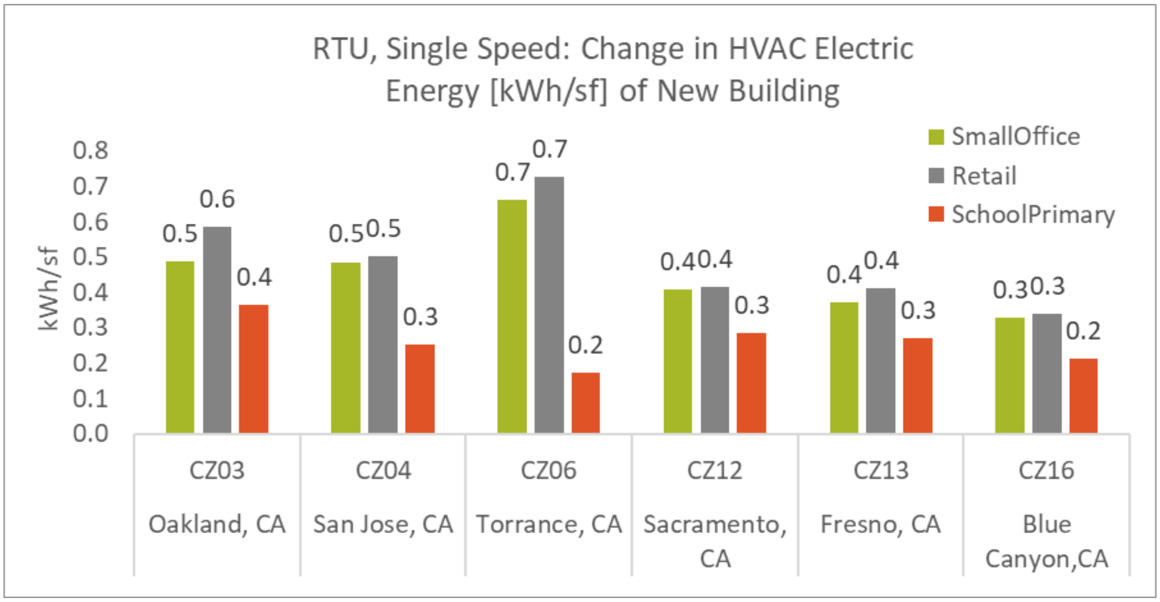

Figure 41: Weighted average increase in HVAC electricity use based on field inspection fault occurrences, single speed RTUs

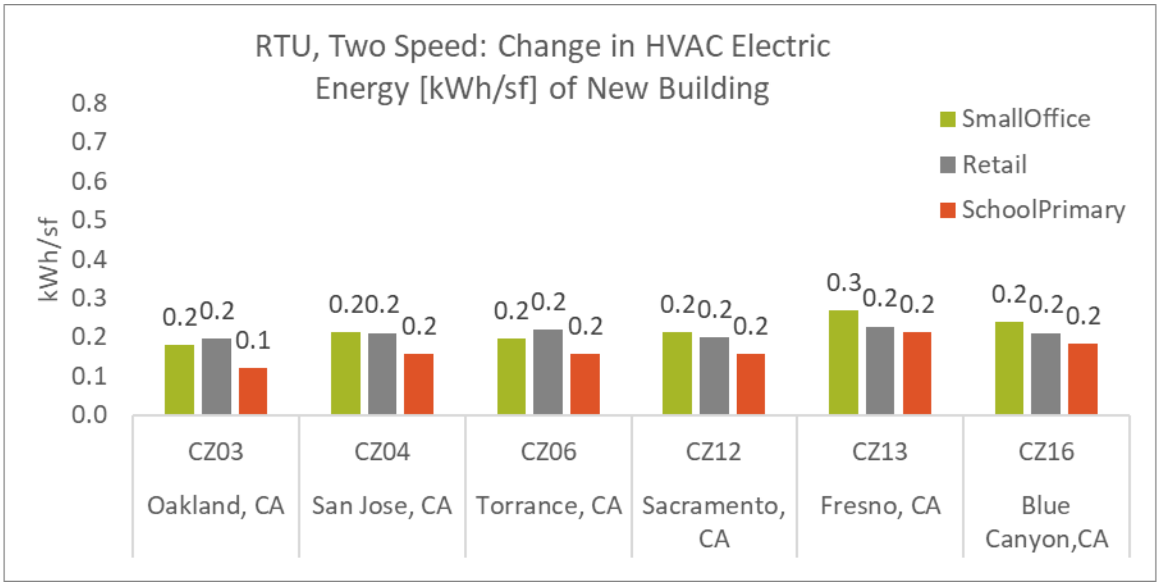

Figure 42: Weighted average increase in HVAC electricity use based on field inspection fault occurrences, two speed RTUs

The Study found that two-speed RTUs had a lower increase in energy use than single-speed RTUs and have more similar nominal impacts across building types and climate regions. On average, two-speed RTUs saw an increase in energy use of 0.2 kWh/sf, with the highest increase being 0.3 kWh/sf. This finding suggests that requiring a wider range of RTU systems to include two-speed fan and two-speed compressor capabilities would reduce the increased energy usage impacts of economizer operational faults.

Figure 43 and Figure 44 show the impacts on energy code compliance of the modeled frequency of fault parameters. For single speed RTUs, the weighted average reduction in code compliance across climate zones and building types was 6%, with a range of 5% and 10% for the three building types. Mild climates, such as Oakland CA, CZ03, show the highest change in code compliance with a 10% reduction for the small school prototype.

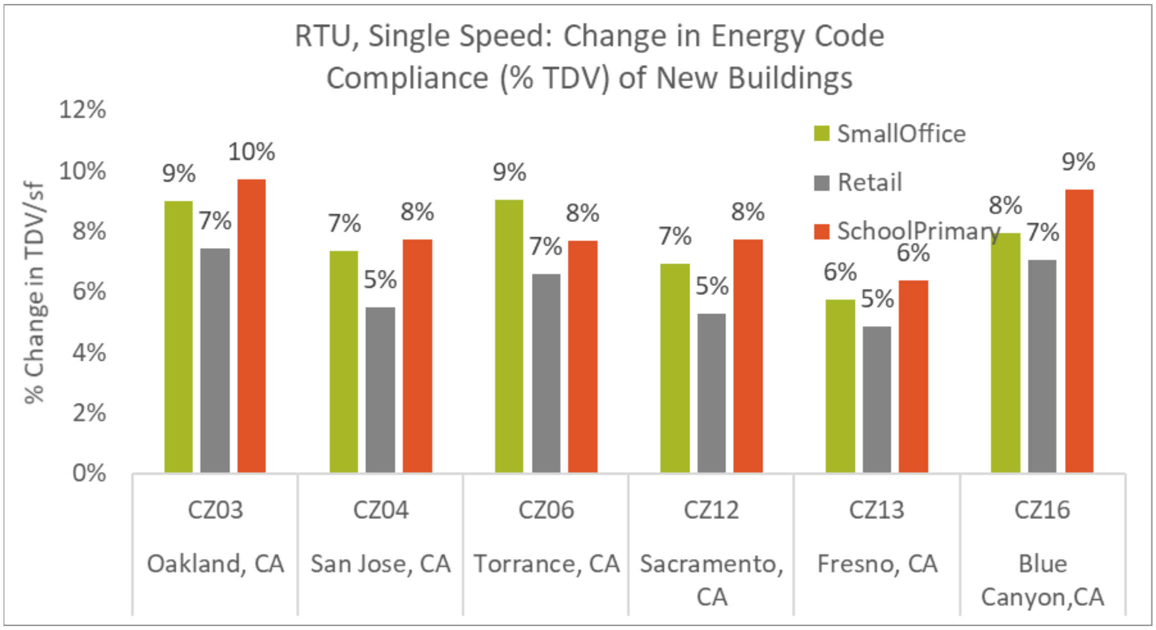

FIGURE 43: WEIGHTED AVERAGE DECREASE IN CODE COMPLIANCE PERCENTAGE BASED ON FIELD INSPECTION FAULT OCCURRENCES, SINGLE SPEED RTUS

In two-speed RTUs, the impact was lower, with an average reduction in energy code compliance of 5%, with a range of 3% to 8% for the three building types.

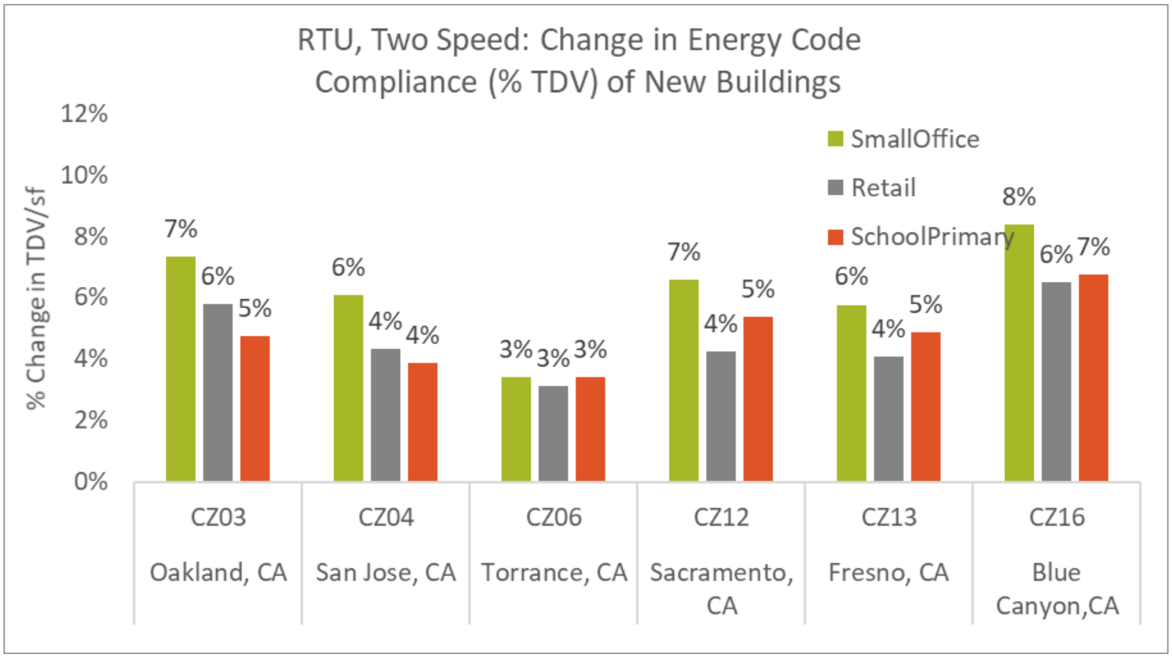

FIGURE 44: WEIGHTED AVERAGE DECREASE IN CODE COMPLIANCE PERCENTAGE BASED ON FIELD INSPECTION FAULT OCCURRENCES, TWO-SPEED RTUS

The simulated results showed minor changes in the buildings' gas usage, with some sites observing a slight decrease in gas usage when the economizer operated with faults. All changes in gas energy use and costs were relatively minor, changing the energy use by less than 0.01 therms/sf. This finding supports the decision to not focus on heating energy impacts of economizers.

FINDINGS: EXPECTED MARKET-WIDE AVERAGE ENERGY IMPACT OF RTU/ECONOMIZER FAULTS COMPARED TO EXPECTED PERFORMANCE PER TITLE 24 REQUIREMENTS.

While the number of systems inspected in the Study represents a smaller sample set of units compared to HVAC 1, this Study provides deeper information on system operation and the types of operational faults and programming errors occurring. To extrapolate the Study findings with greater statistical confidence for estimating the impact of these issues on the average California RTU/economizer performance, the Study Team leveraged the frequency of fault findings from the larger HVAC 1 study sample (246 units). The HVAC 1 study divided the RTU/economizer systems in its sample into three categories: operational, failed, or indeterminate. The Study Team evaluated the results of the Study findings together with the HVAC 1 results to estimate the number of systems operational, operational with some faults, or fully failed in California.

1. This Study considered units from HVAC 1 study found to have passed the inspection (125 units, 73%) and those found to have a failed economizer (47 units, 27%). This accounted for 172 units of the total of the 246 HVAC 1 study data points (i.e., the 74

"indeterminate" units were ignored from the Study analysis because they could not be classified).

2. The Study further sub-divided the proportion of "passed" units from the HVAC 1 study into two categories: "operational and working," and "operational with faults" to account for the field observed operational faults from the Study in units that would have passed the HVAC 1 inspection.
3. The frequency of each of the three types of operational faults modeled in the Study that would have passed the HVAC 1 inspection was adjusted downwards using their respective margins of error. In other words, for each operational fault, the frequency at lower level of confidence (the observed frequency minus the margin of error) was used in the analysis. This conservatism was applied due the small Study sample size.
   a. The economizer programming of the outdoor air setpoint was found to occur 17 out of 26 units (65%) but with the margin of error applied, frequency was modeled at 48%.
   b. The outdoor air minimum damper position being higher than ventilation was observed in 3 of 25 units (12%). Applying the lower bound of the margin of error yielded a frequency of zero, so this very real operational fault--to which overall building compliance was very sensitive--effectively dropped from the extrapolation.
   c. The mixed air temperature sensor location was found to occur in 12 out of 25 sites (48%) for which applying the margin of error results in a frequency of 29%.
4. For the purpose of modeling degraded performance, the Study applied the following operational faults assumptions:
   a. An upper dry bulb control setpoint reduction of 15°F below the required setpoint, which was the most observed scenario
   b. A +2°F bias in the mixed air temperature setpoint control used as a proxy for incorrectly placed sensors.

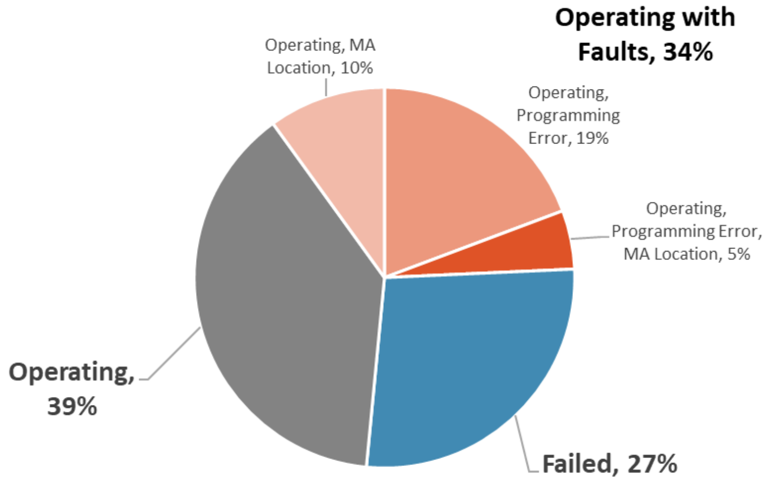

FIGURE 45: THE PERCENT OF UNITS ON A TYPICAL BUILDING WITH RTUS ESTIMATED TO BE OPERATIONAL, OPERATIONAL WITH FAULTS, AND DISABLED WITH REGARDS TO THE ECONOMIZERS

The result of extrapolating the Study observations with the HVAC 1 study findings was that 39% of units are assumed to operate as intended, 34% of units operate with faults, and 27% of units operate with disabled or nonoperational economizers as shown in Figure 45 demonstrates. The Study applied these percentages to the simulated energy modeled scenarios and combined them to estimate the average per-building and per-climate zone impact on operational energy. Figure 46 through Figure 49 present the results. In all figures, positive numbers show the energy increase and labels indicate the absolute and relative increase.

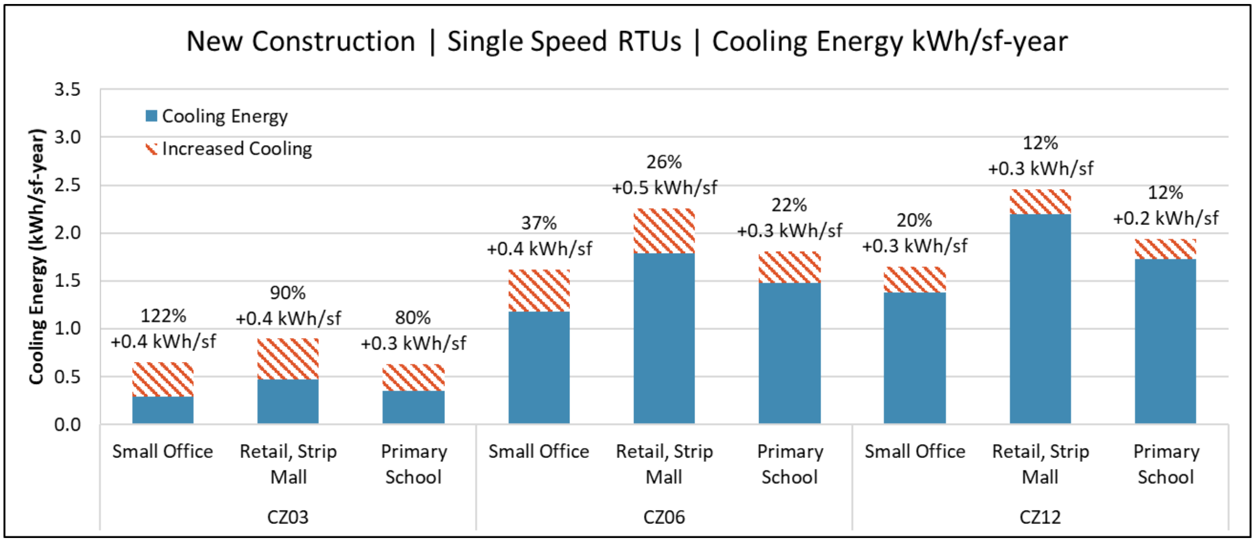

FIGURE 46: WEIGHTED AVERAGE INCREASE IN COOLING ELECTRICAL ENERGY USE BASED ON STUDY RESULTS EXTRAPOLATED WITH HVAC 1 DATA, SINGLE-SPEED RTUS, CZ03, CZ06, AND CZ12

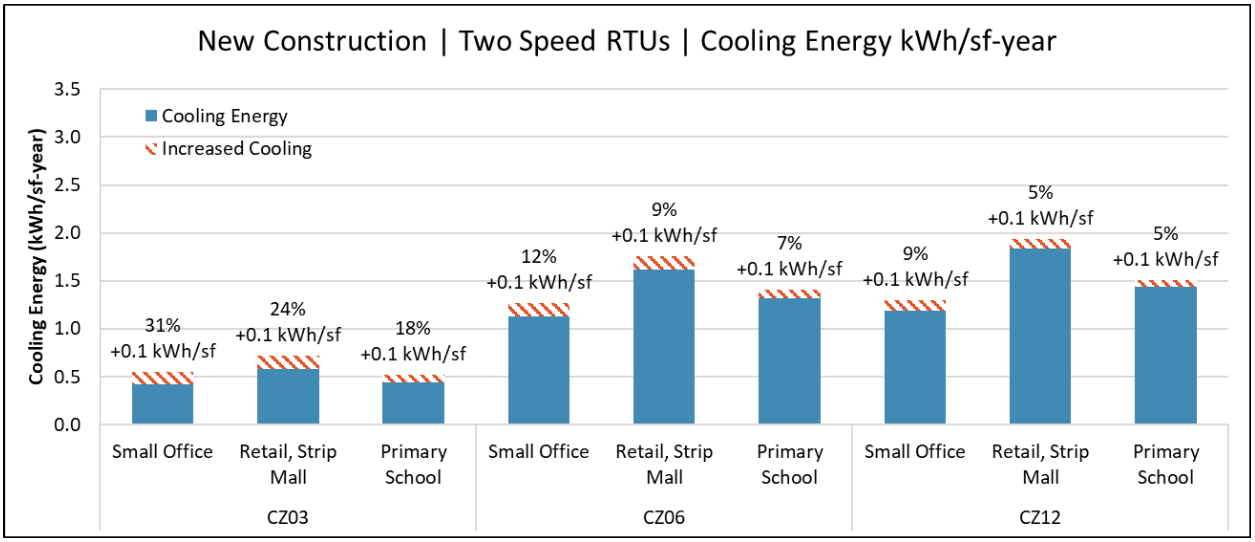

FIGURE 47: WEIGHTED AVERAGE INCREASE IN COOLING ELECTRICAL ENERGY USE BASED ON STUDY RESULTS EXTRAPOLATED WITH HVAC 1 DATA, TWO-SPEED RTUS, CZ03, CZ06, AND CZ12

The average increase in cooling electrical energy for a building with an RTU/economizer across the 6 climate zones was 34% for single-speed RTUs and 11% for two-speed RTUs compared to expected RTU/economizer operation.

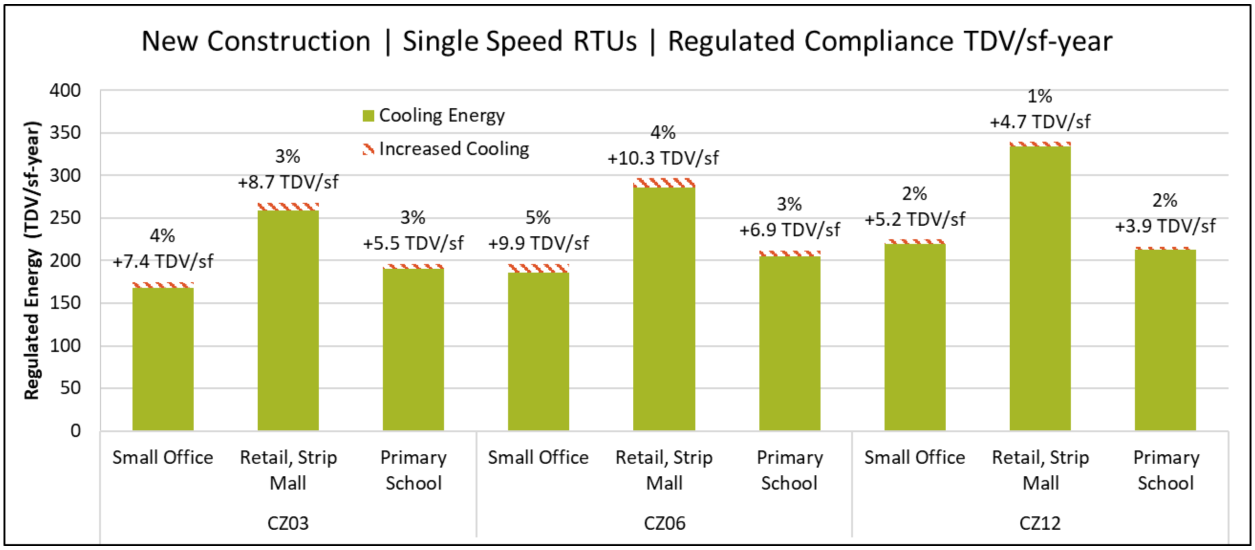

FIGURE 48: WEIGHTED AVERAGE INCREASE IN CODE COMPLIANCE MARGIN TO TITLE 24 2019, BASED ON STUDY FIELD INSPECTION EXTRAPOLATED WITH HVAC 1 STUDY RESULTS, SINGLE-SPEED RTUS, CZ03, CZ06, AND CZ12

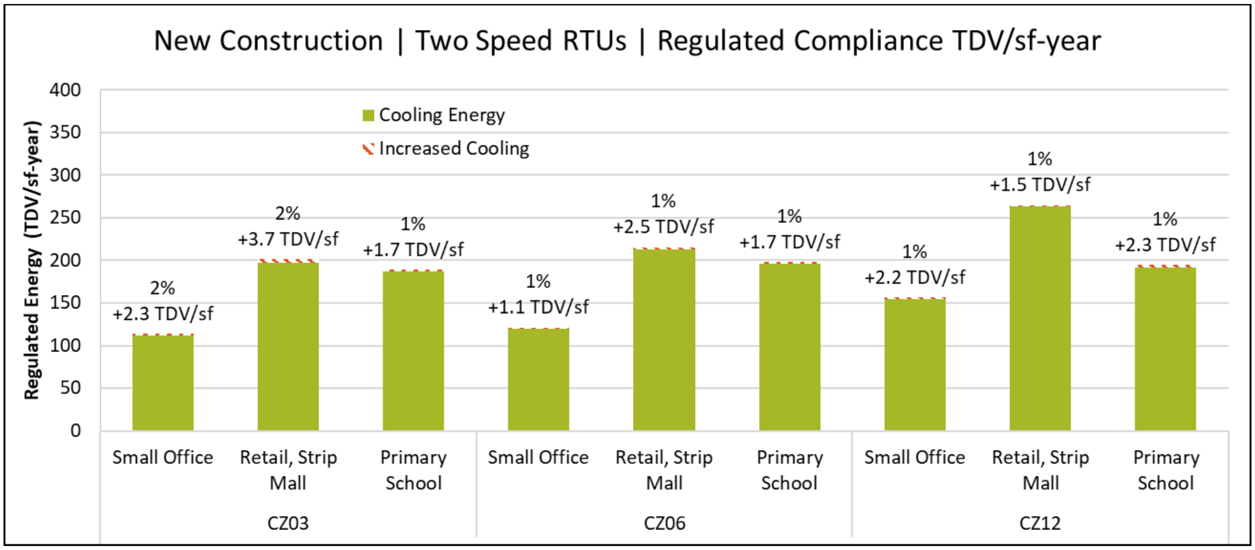

FIGURE 49: WEIGHTED AVERAGE INCREASE IN CODE COMPLIANCE MARGIN TO TITLE 24 2019 BASED ON STUDY FIELD INSPECTION EXTRAPOLATED WITH HVAC 1 STUDY RESULTS, TWO-SPEED RTUS, CZ03, CZ06, AND CZ12

Figure 48 and Figure 49 show the impacts on regulated energy, evaluated with the life cycle cost metric, TDV. Across the six climate zones and three prototype buildings, regulated energy increased by 3% for single-speed RTUs and by 1% in two-speed RTUs.

DISCUSSION AND RECOMMENDATIONS

Consistent with prior research findings for systems installed before the 2014, the Study findings document ongoing and significant underperformance of recently installed RTU/economizer systems in California as compared to expectations embedded in Title 24. In fact, only 3 out of 26 units were properly installed and programmed with economizer controls to correctly modulate from their minimum open position to 100% open during mild outside air conditions. The Study presents key issues below, followed by recommendations in the subsequent section to address the high incidence of suboptimal performing RTU/economizer systems.

DISCUSSION OF IMPLICATIONS FOR CODES & STANDARDS

The following section discusses the six most important implications of the Study.

TITLE 24 ENERGY MODELING PERFORMANCE RULESETS UNDERESTIMATE REAL-WORLD ENERGY USE IN PART-LOAD CONDITIONS

The review of energy modeling part-load performance curves found the current standard Title 24 curve set is the median of all curve sets reviewed for the Study from an annual energy perspective. However, the comparison curve sets show a linear relation between part-load operations and increasing system efficiency at higher part-load conditions while the Title 24 curve sets are nearly flat across all part-load conditions. Further, the Title 24 curves show a flat efficiency at part-loads below 25% where other curves continue to show a reduction in efficiency. These differences in part-load efficiency suggests that Title 24 may significantly underestimate RTU/economizer energy use in climates with part-load conditions.

ECONOMIZER FUNCTIONAL PERFORMANCE ISSUES

The Study's field assessment, as well as the findings of the HVAC 1 study completed in 2017, confirm that despite FDD requirements adopted over three cycles of Title 24, average new RTU/economizer field performance continues to fall short of expectations embodied in Title 24 and CBECC-Com. To a significant degree, the operational faults and programming errors identified in the Study appear to be due to poor installation practices. The majority of RTUs were in basic working order. That is, they could provide basic heating, cooling and ventilation in response to thermostat setpoints. However, only about three-quarters (77%) of units had a functional damper that could modulate in response to outside sensor readings. The remainder had fixed dampers, two in the open position and four in the closed position due to disconnected controllers. This operational fault alone represents a loss of one-quarter of the free cooling potential, on average. Concerningly, only a slight majority of units (54%) met Title 24 minimum fresh air requirements, which raises the risk of occupant comfort, productivity, and health safety problems.

Of the 25 units with active controllers, most (92%) had their outside air sensor installed, but only 60% of the mixed air sensors were installed. Furthermore, while 88% of the outside air sensors were installed and properly positioned, only 52% of mixed air sensors were installed in the correct location (the mixed air plenum). This high rate of improper sensor connection and placement for RTU/economizers installed subsequent to the Title 24 2013 effective date implies a concerning level of system efficiency degradation across the population of RTU/economizers in California.

RTU/Economizer Installer Controller Programming Failures

The Study found a few operational faults which seemed intentional, such as locking a damper in a closed position to minimize smoke concerns during fire season. However, most of the operational faults appeared to be substandard installation practices or suboptimal controller settings made by the installation crew. These would cause significantly higher energy use for the customer and higher than expected system peak demand for the California grid (e.g., from 5:00 to 9:00 p.m.) due to loss of economizing hours.

In the case of programming, 17 of 25 units with controllers were verified with programming errors - either the outdoor air high-limit setpoint was left at the manufacturer's default setting, or for BMS controllers, the setpoint was programmed too low. In all cases the settings are much lower than the high-limit setting required in California.

Given the Study findings the Study team is concerned that there may be widespread misunderstanding of Table 140.4-E in Title 24, Section 140.4. The table specifies a single outdoor air high-limit setpoint for each climate zone; readers may, however, be interpreting the language in the table to mean that their selected high-limit setting need only be equal to or less than the required high-limit setpoint. For example, for Climate Zone 4 (Bay Area), the economizer must shut off when outside air temperature is above 73°F. Therefore, if the high-limit setpoint was programmed to 74°F it would be an obvious failure. However, a high-limit setpoint in the mid-60's may appear acceptable to these installers based on a misunderstanding of the language in the table.

Title 24 does not specify what the economizer controller setpoint default is, but it does require the controller to have high-limit settings that are within 2 degrees of the required high-limit outdoor air setpoint stipulated by Title 24 for each climate zone.

This outcome appears to be a failure, intentional or otherwise, of the installers to program the economizer according to Title 24 requirements. This error leads to significant energy penalties, particularly in climate zones with abundant free cooling opportunities.

Energy Modeling and Analysis

Energy modeling produced estimates of the energy penalty for each type of error found in the field assessment for each of three building types and six representative California climate zones. This energy penalty was then weighted by the frequency of the different operational faults and programming errors presumed to be occurring in the overall population of RTU/economizers. When taken together, the analysis shows that on average, performance degradation reduces expected RTU/economizer performance by 30% for cooling energy and reduction in whole building code compliance of 2%, based on TDV.

Almost all the observed operational faults were a result of installation and field configuration errors that did not properly set up RTU/economizer systems to meet the California energy standard. In addition, there were improper or missing inspections of these units during required acceptance tests, which are meant to identify these errors. RTU/economizers represent the baseline system against which project code compliance and code enhancements are compared to determine relative energy savings and cost-effectiveness. The overly optimistic HVAC performance baseline creates a disincentive for properly installed, alternative HVAC technologies.

The Study Team intended to inspect a generally representative sample of RTU/economizer units for California climates. However, due to the scale of the Study, there was no expectation that the ~30 unit sample would be big enough to produce statistically robust findings that alone allow the Study Team to confidently characterize what impact would be expected in an average California building. The HVAC 1 study was the most comparable study on RTU field performance with statistically significant results; the HVAC 1 study's large sample size achieved a 90% confidence (+/- 8%) level for PG&E's service territory. Though the HVAC 1 study design informed the development of the Study field assessment protocols, the frequency of operational faults found in the Study was significantly worse than those found in the HVAC 1 study.

This small sample's lack of statistical significance (26 units) led the Study Team to leverage the more conservative and statistically robust HVAC 1 findings (for 246 units) regarding operational fault frequency. With this information, the Study Team calibrated the frequency of the operational faults model when assessing the overall average energy efficiency degradation in California reported above.

Though the HVAC 1 study informed the Study's filed assessment protocol, the Study reported more detailed information than the HVAC 1 study. Notably, the Study collected data on the field programming of economizer controllers, or lack thereof, which was not reported in the HVAC 1 study. For that reason, the Study modeling analysis of average statewide impacts was able to incorporate this important, additional data on operational faults and programming error frequency rates. In extrapolating the frequency of programming errors found in the Study field assessment, the Study Team used programming error frequency defined by the bottom bound of the margin of error of the frequency in Study sample. The Study modeled the extrapolated operational faults and programming errors as described in the previous two paragraphs to increase confidence in the Study findings and recommendations. Thus, the 47% and 30% average increase in cooling energy for single-speed and two-speed RTUs, respectively, likely represents a conservative estimate of incremental average energy use due to the faults and errors.

Fault Diagnostic & Detection

The Study found that economizer controllers met the system status and fault requirements but typically did not comply with the reporting requirements. The primary reason for FDD compliance failure was that installed thermostats did not comply with the "annunciated locally on one or more zone thermostats, or a device within five (5) feet of zone thermostat(s)" requirement. As a result, occupants were typically unaware when units were in alarm. Even when they did comply with this requirement, the following conditions degraded the effectiveness of FDD:

1. Required contact information for the HVAC service provider and instructions on what to do in the event of an active alarm was not found at any sites.
2. Even with visible alarms in the zone, it was unclear what the specific alarm condition was since the only indicator of a problem was an active light. Therefore, the only way

to determine the particular cause of an alarm was to access the economizer controller, within the unit, on the roof, and scroll through the menu options.

For FDDs to be effective as intended, users must be trained to call for service when an alarm is active. Service personnel must then know how to identify active alarms at the economizer controller menu. They must then correct the error and manually clear the alarm. The findings indicate that installation and setup errors that are not addressed during construction will likely persist throughout the unit's life.

ACCEPTANCE TESTS

The Study considered two fundamental questions related to acceptance tests:

- **Was the acceptance testing completed and valid?**
- **Are the acceptance test protocols adequate to prevent the operational faults and errors observed in this Study?**

Very few sites were able to provide Title 24 compliance documentation. In addition, most sites did not have completed acceptance forms, and few building owners kept comprehensive design documents. This led the Study Team to infer that most building inspectors were not enforcing acceptance testing requirements because most sites with installation faults and programming errors would have failed the 2013 and 2016 acceptance tests.

The Study Team believes that the updates in the Title 24-2019 MCH-05 acceptance test form can significantly improve the outcomes if the form is faithfully completed. The 2019 acceptance testing process would have identified all observed operational faults and programming errors present at the time of installation. As of April 14th, 2021, there were 300 certified mechanical acceptance testers (this was the threshold to enforce the Mechanical Acceptance Test requirements). The "Authority Having Jurisdiction" will now require a certified "Mechanical Acceptance Test Technician" to fill out the forms for all projects submitted after October 1st, 2021.

However, it is essential to note that the forms are only as good as the information provided by the person filling them out. Four entities that may certify mechanical acceptance test technicians are:

- California State Pipe Trades Council
- National Energy Management Institute Committee (NEMIC)
- National Environmental Balancing Bureau (NEBB)
- Refrigeration Service Engineers Society (RSES)

The 2019 MCH-05 acceptance test form will support improved compliance outcomes if accompanied by increased technician training and jurisdiction enforcement. Additionally, requiring certifying agency to perform quality assurance protocols is expected to increase the validity of acceptance testing. The adoption of requirements in Title 24-2022 that new RTU units below 33,000 Btu/h must have economizers will result in smaller RTUs being installed with economizer controls which will increase the importance acceptance testing.

Recommendations for Codes & Standards Enhancements

Based on the Study findings and discussion above, the Study Team makes the following recommendations:

1. Code compliance rule sets for RTU/economizers in the energy code simulation compliance option and the prescriptive compliance pathway allowances in the energy code yield better energy efficiency than is realistic in California.

   Recommendation: Simulation rulesets should be adjusted to reflect ~~a~~ deration in the efficiency of RTU/economizer systems to levels found by the Study.

2. Simulation representation of part load performance of RTU/economizer systems for both single-speed and two-speed RTU must continue to be advanced to accurately represent the available products as well as changes or improvements being implemented.

   Recommendation: Perform laboratory and field investigations to determine how typical RTU/economize systems operate at lower part-loads. The differences in internal componentry and controls that drive these differences need to be understood to ensure that performance curves relied on for compliance purposes reasonably reflect the part-load performance of RTU/economizers in California. Based on the findings of this additional investigation the performance curves used by CBECC-Com may need to be adjusted to reflect typical part-load performance better.

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ACRONYMS

AMY/TMY	Actual/Typical Meteorologic Year (for building energy modeling)
BMS	Building Management System
BTUh	British Thermal Unit per Hour
CALMAC	California Measurement Advisory Council
CBECC	California Building Energy Code Compliance
CEC	California Energy Commission
CFM	cubic feet per minute
CZ	climate zone
DOE	US Department of Energy
DX	direct expansion
°F	Degrees Fahrenheit
FDD	Fault Detection Diagnostics
FPT	Functional Performance Test Procedures
ft^2	square feet (as a measure of conditioned area)
HVAC	Heating, Ventilation, and Air Conditioning
kWh	kilowatt hour
MCH	Mechanical (as abbreviated in compliance forms)
PIER	Public Interest Energy Research
PG&E	Pacific Gas and Electric Company
PNNL	Pacific Northwest National Laboratory
RTU	Rooftop Unit
TDV	Time Dependent Value
UC	University of California
WCEC	Western Cooling Efficiency Center (at the University of California, Davis)

APPENDICES

APPENDIX A: RTU DX PERFORMANCE CURVE COEFFICIENTS

Curve Function	Curve Name	a	b	c	d	e	f
Total Cooling Capacity modifier function of temperature $C_{ap}(T_{wb,I},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{c,i})(T_{wb,i})$	PNNL Lennox	4.24E-01	4.43E-02	-4.20E-04	3.33E-03	-8.00E-05	-2.10E-04
	PNNL Carrier	1.39E+00	-5.29E-02	1.84E-03	5.83E-04	-1.87E-04	2.65E-04
	PNNL Generic	7.67E-01	1.08E-02	-4.15E-05	1.35E-03	-2.61E-04	4.57E-04
	Goodman	1.30E+00	-6.18E-02	2.47E-03	8.16E-03	-1.83E-04	-1.61E-04
	York Affinity	1.23E+00	-3.99E-02	1.94E-03	6.21E-03	-1.25E-04	-3.62E-04
	York Predator	1.21E+00	-2.88E-02	2.23E-03	1.97E-03	-5.41E-05	-7.39E-04
	York Sunline ZR060	1.15E+00	-1.61E-02	1.59E-03	-2.77E-03	-2.36E-05	-4.69E-04
	York Sunline ZF240	1.05E+00	-1.27E-02	1.28E-03	1.24E-03	-5.51E-05	-3.88E-04
	NREL_Single Speed	1.55E+00	-7.51E-02	3.10E-03	2.40E-03	-5.00E-05	-4.30E-04
	CoilClgDX_TS	8.68E-01	1.42E-02	5.54E-04	-7.57E-03	3.20E-05	-1.91E-04
	NRELTwo Speed – High Speed	1.37E+00	-6.26E-02	2.80E-03	5.04E-03	-7.00E-05	-4.50E-04

Curve Function	Curve Name	a	b	c	d
Total cooling capacity modifier function of flow fraction Cap(ff) = a + b(ff) + c(ff)2	PNNL Lennox	7.71E-01	3.41E-01	-1.11E-01	
	PNNL Carrier	7.19E-01	4.35E-01	-1.54E-01	
	PNNL Generic	8.00E-01	2.00E-01		
	Goodman	-9.36E-01	3.44E+00	-1.51E+0	
	York Affinity	1.25E+00	-7.18E-01	4.62E-01	
	York Predator	6.74E-01	4.70E-01	-1.47E-01	
	York Sunline ZR060	3.15E-01	1.05E+00	-3.71E-01	
	York Sunline ZF240	6.04E-01	6.56E-01	-2.67E-01	
	NREL_Single Speed	8.00E-01	2.00E-01		
	CoilClgDX_TS	4.73E-01	1.24E+00	-1.04E+0	3.22E-01
	NRELTwo Speed-High Speed	8.00E-01	2.00E-01		

Curve Function	Curve Name	a	b	c	d	e	f
EIR modifier function of temperature $EIR(T_{wb,I},T_{c,i}) = a + b(T_{wb,i}) + c(T_{wb,i})^2 + d(T_{c,i}) + e(T_{c,i})^2 + f(T_{c,i})(T_{wb,i})$	PNNL Lennox	1.24E+00	-2.43E-02	5.70E-04	-1.43E-02	6.30E-04	-3.80E-04
	PNNL Carrier	-5.36E-01	1.05E-01	-1.73E-03	1.50E-02	6.60E-04	-1.74E-03
	PNNL Generic	2.97E-01	4.31E-02	-7.49E-04	5.98E-03	4.82E-04	-9.56E-04
	Goodman	1.62E-01	5.32E-02	-1.56E-03	7.76E-03	1.86E-04	-1.39E-04
	York Affinity	-1.27E-01	8.48E-02	-2.11E-03	-8.58E-03	7.78E-04	-5.59E-04
	York Predator	4.82E-01	4.02E-02	-1.58E-03	-1.16E-02	6.76E-04	-1.20E-04
	York Sunline ZR060	1.21E-01	5.61E-02	-1.23E-03	9.28E-03	6.00E-04	-1.05E-03
	York Sunline ZF240	4.54E-01	2.14E-02	-7.05E-04	2.87E-03	4.21E-04	-3.18E-04
	NREL_Single Speed	-3.00E-01	1.10E-01	-3.42E-03	-6.26E-03	7.00E-04	-4.30E-04
	CoilClgDX_TS	1.16E-01	2.85E-01	-4.11E-04	2.14E-02	1.62E-04	-6.80E-04
	NRELTwo Speed – High Speed	-4.23E-02	7.89E-02	-2.38E-03	-3.04E-03	5.30E-04	-3.20E-04

Curve Function	Curve Name	a	b	c	d
EIR modifier function of flow fraction $EIR(ff) = a + b(ff) + c(ff)^2$	PNNL Lennox	1.21E+00	-3.30E-01	1.23E-01	
	PNNL Carrier	1.20E+00	-3.06E-01	1.11E-01	
	PNNL Generic	1.16E+00	-1.82E-01	2.56E-02	
	Goodman	2.29E+00	-2.29E+0	1.00E+00	
	York Affinity	6.53E-01	8.19E-01	-4.62E-01	
	York Predator	1.31E+00	-4.42E-01	1.38E-01	
	York Sunline ZR060	1.97E+00	-1.63E+0	6.69E-01	
	York Sunline ZF240	1.44E+00	-7.57E-01	3.24E-01	
	NREL_Single Speed	1.16E+00	-1.82E-01	2.56E-02	
	CoilClgDX_TS	1.01E+00	3.45E-01	-6.92E-01	3.39E-01
	NRELTwo Speed – High Speed	1.16E+00	-1.82E-01	2.56E-02	

Curve Function	Curve Name	a	b	c	d
Part-load correction function PLF(PLR) = a + b(PLR) + c(PLR)2	PNNL Lennox	7.71E-01	2.29E-01		
	PNNL Carrier	7.71E-01	2.29E-01		
	PNNL Generic	8.50E-01	1.50E-01		
	Goodman	8.50E-01	1.50E-01		
	York Affinity	8.50E-01	1.50E-01		
	York Predator	8.50E-01	1.50E-01		
	York Sunline ZR060	8.50E-01	1.50E-01		
	York Sunline ZF240	8.50E-01	1.50E-01		
	NREL_Single Speed	8.50E-01	1.50E-01		
	CoilClgDX_TS		5.11E+00	-8.55E+0	4.47E+00
	NRELTwo Speed – High Speed	8.50E-01	1.50E-01		

Appendix B: Site Visit Detail Table

Site No.	Site Type	Clim. Zone	RTU Make	Manu. MM/YY	Unit Tons	Econ. Model	High Limit Setpoint (°F)	Econ. Min. Pos. (%)	Damper Opera-tion	Free Cooling Pass/ Fail	Met Sys. Status	Met Sys. Fault	Met Rptg.	Pass / Fail	Reporting Method
2	Gymnasium	12	York	Unknown	12.5	ECO	55	0	Can modulate	Fail	1	1	0	Fail	No alarm at T-stat
2	Gymnasium	12	York	Unknown	12.5	ECO	55	0	Can modulate	Fail	1	1	0	Fail	No alarm at T-stat
3	Church	12	Daikin	Unknown	5	None	None	None	Fixed Open	Fail	0	0	0	Fail	No alarm at T-stat
4	Office	12	Bryant	01/16	5	Jade	63	0	Can modulate	Fail	1	1	0	Fail	No alarm at T-stat
5	Gymnasium	12	York	Unknown	7.5	ECO	55	0	Can modulate	Fail	1	1	0	Fail	No alarm at T-stat
5	Gymnasium	12	York	Unknown	7.5	ECO	55	0	Can modulate	Fail	1	1	0	Fail	No alarm at T-stat
6	Office	13	Carrier	Unknown	12.5	Jade	None	0	Failed closed	Fail	0	0	0	Fail	No alarm at T-stat
7	Conference Rooms	4	Trane	09/17	6	ReliaTel	72	10	Can modulate	Pass	1	1	1	Pass	Alarm at BMS
7	Conference Rooms	4	Trane	09/17	6	ReliaTel	72	10	Can modulate	Pass	1	1	1	Pass	Alarm at BMS
8	Medical Office	4	JCI	Unknown	6.5	ECO	55	17	Can modulate	Fail	1	1	1	Pass	Text to service provider
8	Medical Office	4	JCI	Unknown	6.5	ECO	55	17	Can modulate	Fail	1	1	1	Pass	Text to service provider
8	Medical Office	4	JCI	Unknown	7.5	ECO	55	17	Can modulate	Fail	1	1	1	Pass	Text to service provider
9	Gymnasium	12	York	01/15	10	Jade	63	0	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat

Site No.	Site Type	Clim. Zone	RTU Make	Manu. MM/YY	Unit Tons	Econ. Model	High Limit Setpoint (°F)	Econ. Min. Pos. (%)	Damper Opera-tion	Free Cooling Pass/ Fail	Met Sys. Status	Met Sys. Fault	Met Rptg.	Pass / Fail	Reporting Method
9	Gymnasium	12	York	01/15	10	Jade	63	0	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat

Site No.	Site Type	Clim. Zone	RTU Make	Manu. MM/YY	Unit Tons	Econ. Model	High Limit Setpoint (°F)	Econ. Min. Pos. (%)	Damper Opera-tion	Free Cooling Pass/ Fail	Met Sys. Status	Met Sys. Fault	Met Rptg.	Pass / Fail	Reporting Method
9	Gymnasium	12	York	01/15	10	Jade	63	0	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat
10	Restaurant	12	Carrier	04/20	5	Jade	63	12	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat
10	Restaurant	12	Carrier	04/20	5	Jade	63	12	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat
11	Lab Space	4	Trane	06/14	6	ReliaTel	None	15	Fixed open	Fail	1	0	1	Fail	No alarms programmed
12	Office	4	Trane	07/12	6	ReliaTel	N/A*	0	Failed closed	Fail	1	0	1	Fail	No alarms programmed
12	Office	4	Trane	07/12	6	ReliaTel	N/A*	0	Failed closed	Fail	1	0	1	Fail	No alarms programmed
12	Office	4	Trane	07/12	6	ReliaTel	N/A*	0	Failed closed	Fail	1	0	1	Fail	No alarms programmed
13	Cafeteria	4	Trane	11/14	12.5	ReliaTel	N/A**	20 (est)	Can modulate	Fail	1	0	1	Fail	No alarms programmed
14	Office	3	Trane	04/19	6.5	ReliaTel	60	10	Can modulate	Fail	1	0	1	Fail	No alarms programmed
14	Office	3	Trane	04/19	6.5	ReliaTel	68	10	Can modulate	Pass	1	0	1	Fail	No alarms programmed
15	Dorm Common Area	12	JCI	04/21	10	ECO	55	45	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat

15	Dorm Common Area	12	JCI	04/21	10	ECO	55	45	Can modulate	Fail	1	1	1	Pass	Aux. Alarm to T-stat

ATTACHMENTS

The following attachments are separate documents.

ATTACHMENT A: FUNCTIONAL PERFORMANCE TEST PROCEDURES

ATTACHMENT B: MODELING APPROACH DETAIL