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Smart Ventilation for Advance California Homes – Single Zone Technology Task

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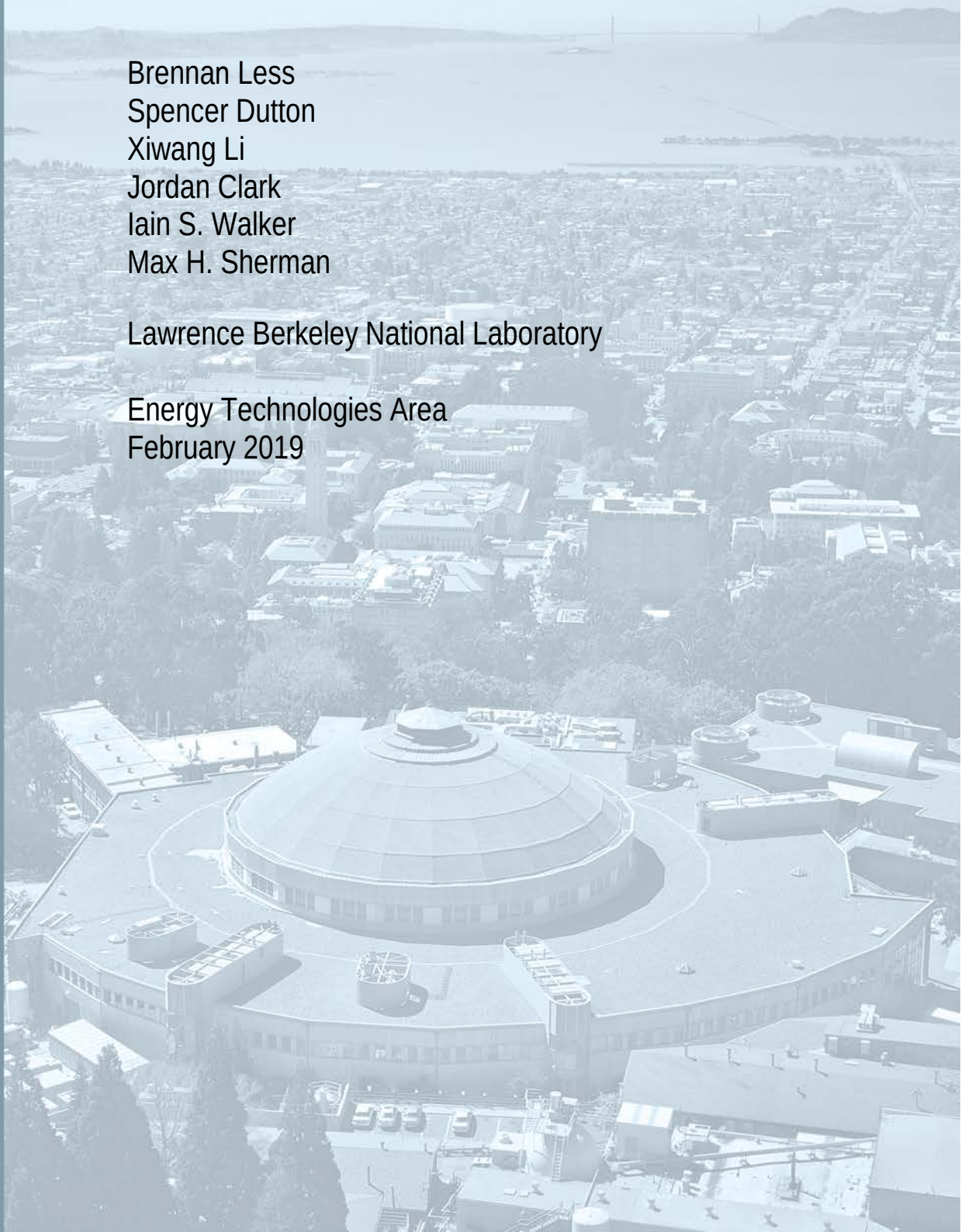

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Abstract

This study is intended to demonstrate the potential for energy savings while providing acceptable Indoor Air Quality (IAQ) for ZNE homes. It uses the concept of Smart Ventilation where ventilation systems are designed and controlled to produce the same, or better, IAQ compared to simple, continuously operated ventilation systems. The key energy saving principle for smart ventilation is that ventilation is shifted in time to when the energy required to condition the air is lower. A variety of smart ventilation controls based on outdoor temperature, occupancy and auxiliary fan sensing were developed and assessed across homes built to the 2016 Title 24 Prescriptive standards in California climate regions. Simulations used a co-simulation strategy that combines EnergyPlus with CONTAM. The IAQ calculations were based on the equivalent ventilation principle outlined in the ASHRAE 62.2-2016 ventilation standard, Appendix C. Two prototype homes were simulated (1-story 2,100 ft^2 and 2-story 2,700 ft^2). Their envelope airtightness was varied between 1, 3 and 5 ACH_{50}. Climate zones were chosen to reflect the variety of heating and cooling demand throughout California. A weighted average analysis was used to generalize the energy predictions across the projected new housing stock in the state. Temperature-based controls were found to be effective, with the most successful smart controls reducing weighted average site ventilation energy use by about 40%, while TDV weighted average ventilation energy reductions were higher, up to roughly 60%. Results were also normalized to ensure identical IAQ in all cases, and the weighted average site and TDV ventilation savings increased, up to 55% and 72% ventilation savings, respectively, for the top-performing temperature-based controls. Peak demand during the 2-6pm period on the hottest days of the year was reduced by up to 400 watts. More than 90% of site energy savings were for heating end-uses, while TDV energy savings were split fairly evenly between heating and cooling. On average, the smart controls reduced occupant pollutant exposure by 0-10%, and they increased ventilation rates by roughly 20%. Occupancy-based controls that accounted for contaminants released by building materials and furnishings during unoccupied times were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls. All temperature and occupancy controls were also tested with auxiliary fan sensing capability (i.e., accounting for the use of other exhaust devices in the home, like bathroom or kitchen fans). Auxiliary fan sensing increased energy savings in all cases, from roughly 5 to 15%.

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1 Introduction

Ventilation is the intentional exchange of outside air with the air inside a conditioned space. Its purpose is to displace pollutants of indoor origin such as human bioeffluents, emissions from consumer products and building materials, products of combustion, by-products from cooking and other sources. Ventilation also contributes to a building's energy balance, and thus can be either a driver of energy consumption, or a means of reducing energy use when outdoor conditions are favorable.

Research on how best to ventilate buildings is motivated by several factors. First, increased recognition and awareness of the substantial public health burden that results from exposure to contaminants of concern in indoor environments. Logue et al. (2011) estimated the number of disability-adjusted life years lost per 100,000 people in U.S. residences as a result of exposure to indoor pollutants on the order of 1,000 from fine particulate matter alone, and on the order of 10-100 for both formaldehyde and acrolein.

Second, these exposures are becoming even more important in the context of energy efficiency requirements in building codes and voluntary standards that require substantial air leakage reductions, compared with homes of the past. For example, in many U.S. climates, the International Energy Conservation Code (IECC) requires an envelope leakage rate of 3 ACH_{50} (ICC, 2012), and select voluntary programs, such as Passive House, require extreme airtightness at <0.6 ACH_{50}. New California homes are typically in the range of 4-6 ACH_{50} (Chan, Kim, Less, Singer, & Walker, 2018). Typical values for new homes even a decade ago were in the range of 6-10 ACH_{50}, while older, existing homes range from 10-30 ACH_{50} (Chan, Joh, & Sherman, 2013).

In this context, codes and standards have begun to require mechanical ventilation in residences. Airflow requirements vary, but most standards in the U.S. are based on current or previous versions of the ASHRAE 62.2 ventilation standard. For example, all new homes in California have been required to provide whole house dilution ventilation since 2008 (California Energy Commission, 2008). Similar requirements exist in the IECC and in select state energy codes and voluntary programs (e.g., State of Washington Energy Code). Without dedicated ventilation systems, concentrations of indoor pollutants in advanced California homes would be significantly higher than their older, leakier counterparts.

Third, increasing ventilation at times when outdoor conditions are favorable is increasingly being understood as a viable means of providing energy-efficient thermal control. Strategies include passive cooling via natural ventilation, the use of

economizers, and (as this study explores) modulation of dedicated ventilation in response to outdoor temperatures.

Finally, stress on the electric power grid is a major concern as mechanical cooling and renewable energy saturation increases in California homes and businesses. Ventilation loads are greatest at times of day, and times of the year, when the grid is already stressed the most, or when rapid ramping of supply is needed (late afternoon and evening). Shifting ventilation to times of lower grid demand may provide substantial benefit.

Given these motivations, this study explores possible approaches to providing ventilation that both ensures acceptable indoor air quality, and minimizes the energy penalty associated with conditioning ventilation air. As implemented in this work, smart strategies do not require direct sensing of individual pollutants of concern[1]; instead, all IAQ considerations use the concept of *relative exposure* to a continuously emitted, indoor generic pollutant. Smart controls must maintain annual average exposure to this contaminant that is that same as would be achieved by a continuous fan sized to the ASHRAE 62.2 ventilation standard.

Specifically, we look at "smart" ventilation strategies that involve modulating ventilation rates throughout the course of a day or year. These strategies may respond to outdoor air temperature, occupancy detection, predicted exposures, and the operation of auxiliary ventilation devices such as bathroom fans. The recent explosion in Internet of Things research and development has paved the way for such a means of controlling buildings to be possible. A thorough review of available smart ventilation strategies that have been previously studied can be found in I. Walker, Sherman, Clark, & Guyot (2017).

Past work has used related approaches to develop and assess smart ventilation controls in homes in a variety of climates. A controller named RIVEC (short for **R**esidential **I**ntegrated **Ven**tilation **C**ontroller) was developed and briefly field-tested in California that used occupancy, auxiliary fan sensing, grid signals and timer-based temperature controls (Iain S. Walker, Sherman, & Dickerhoff, 2012). Less, Walker, & Tang (2014) studied the effects of several temperature-based control strategies that used cut-off temperatures below which IAQ fans were turned off (fan airflow were increased during all other hours). Smart controls for humidity control in hot and warm-humid climates were developed for similar homes in Less, Walker, & Ticci (2016). Less & Walker (2017) examined the performance of occupancy and auxiliary fan smart controls in Zero Energy Ready homes across U.S. DOE climate regions. Finally, work at the Florida Solar Energy Center (Martin, Fenaughty, & Parker, 2018) has developed a multi-parameter smart ventilation controller using outdoor temperature and moisture levels, paired with pre-

[1] The next phase of our work will look at strategies that involve sensing of individual pollutants.

calculated seasonal ventilation targets. They also reported on limited field-testing of an occupancy-based smart controller deployed in a Deep Energy Retrofit home in the Pacific Northwest.

Concurrently, more and more consumer building products are emerging on the market that provide some form of ventilation control based on measured temperature and humidity, but which do not track relative exposure to preserve IAQ, and are not compliant with codes and standards. An incomplete descriptive list of these products is provided in Table 39 in Appendix T, including summaries of cost, sensor options and control schemas. Products are diverse, costing between $50 and $300. They include a variety of either indoor or outdoor (or both) temperature and/or humidity sensors, and many are limited to use with certain fan types, or are embedded within certain fan technologies. Some controllers have hot-humid climate control features, but lack cold climate features. This brief review suggests that products are available and can be economically integrated with systems, sensors and varied control features; what they lack are optimized controls that maintain compliance with ventilation codes and standards.

While past work has explored smart controls broadly in U.S. climates, this study considers only advanced homes in the State of California, defined as homes that conform to the 2016 Title 24 energy efficiency standard. This study looks only at homes with dedicated mechanical ventilation, and does not explore natural ventilation strategies. All of the analyses use detailed annual simulations of reference buildings with thermal and airflow characteristics of homes built to the 2016 Title 24 standard, under a variety of different ventilation control strategies, described in the next chapter. All homes are considered well-mixed zones for the current work. Multi-zone approaches will be studied in detail in a subsequent phase.

With this in mind, we pursued three objectives:

1. Provide guidance to the building community, and the State of California, on the most effective means of sizing and controlling ventilation fans in high-performing California homes.

2. Estimate the energy savings available with different Smart Ventilation controls.

3. Assess the effects of Smart Ventilation controls on occupant exposure to pollutants of indoor origin.

Sections 3.1 through 3.5 describe the smart ventilation control strategies we analyzed in this work. Section 4 outlines the modeling and analysis methods, and Section 5 present the primary energy results. The final Sections 6 and 7 discuss these results, present conclusions, and provide guidance.

2 Smart Ventilation, Relative Exposure and Airflow

In this work, we investigate smart ventilation control (SVC) strategies in advanced California homes. The goal of SVC is to improve home performance in comparison to a baseline continuous fan, in terms of both IAQ and energy use.

The IAQ analysis presented in this work uses the concept of *relative exposure*. This is an approach for assessing the IAQ performance of variable ventilation strategies (Max H. Sherman, Mortensen, & Walker, 2011; Max H. Sherman, Walker, & Logue, 2012). Relative exposure assesses the relative concentration of a generic pollutant emitted at a constant rate indoors, with no outdoor sources and no non-ventilation removal processes (e.g., deposition, filtration, etc.). The metric compares the concentration of that pollutant under time-varying versus continuous ventilation schemes. Over short time periods (i.e., about the time needed to replace all the air in the building), a relative exposure of 1 means the two ventilation rates are equal. Averaged over longer periods (e.g., annually), a value of 1 means the two ventilation strategies provide equivalent pollutant exposure—even though the instantaneous ventilation rates may vary dramatically. Values less than one reflect over-ventilation relative to the reference airflow rate (lower pollutant exposure), while values above one reflect under-ventilation (higher pollutant exposure).

Relative exposure is the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard. The standard requires that exposure be estimated at each time step of the assessed period, which in this work was once every 5-minutes. Annually, the arithmetic mean of the relative exposure during occupied hours must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 requirements. A value of one implies that the annual mean occupied exposure to the generic contaminant is the same as would have occurred if the house were ventilated continuously at the whole house target airflow (Qtotal) calculated in 62.2-2016. These cases are said to be "equivalent". Note: use of this new approach is limited, as most homes comply using either a continuous or timer-controlled fan that is sized using simple equations or lookup tables.

Under steady-state conditions, the indoor concentration due to an indoor source, and with no removal other than by ventilation, is inversely proportional to the ventilation rate. As a result, the airflow increase required to reduce the concentration by some marginal amount Δc is much greater than the reduction in airflow needed to increase the concentration by Δc. For example, a home ventilated at 0.5 air changes per hour (ACH, hr^{-1}) and a formaldehyde concentration of 30 ppb would need to double its airflow, to 1 ACH, in order to halve the concentration to 15 ppb. But the same house would reach 45 ppb (30 + 15) after only a 33% reduction in the ventilation rate, from 0.5 to 0.23 ACH. Thus it can cost more to reduce a pollutant concentration than is saved by allowing the concentration to increase in the first place. This effectively biases time-varying ventilation patterns towards overall higher airflow rates (when maintaining equivalence, i.e., the same long-term

mean concentration), which must be compensated for by increasing airflow when the energy penalty for doing so is small. Controllers that fail to do this may have limited value.

All of the control strategies are designed to comply with the calculation methods and requirements in ASHRAE Standard 62.2-2016 Appendix C. The relative exposure (R_i) for a given time step is calculated from the whole house target ventilation rate (Q_{tot}), the current house ventilation rate (Q_i), and the relative exposure from the prior step (R_{i-1}). The current house ventilation rate (Q_i) is either a controller estimated value ("controller") or the result of the CONTAM mass balance ("real").

In this work, the target ventilation rate used in IAQ calculations for all cases is the Total Required Ventilation Rate (Q_{tot}) from ASHRAE Standard 62.2:

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{bed} + 1) \quad (1)$$

where A_{floor} is the floor area of the house (m^2), N_{bed} is the number of bedrooms, and Q_{tot} is in liters per second (L/s).

Using the estimated whole house airflow (calculation described below), the relative exposure is calculated at each time step using Equation 2.

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t/V_{space}}} \quad (2)$$

R_i = relative exposure for time-step, i
R_{i-1} = relative exposure for previous time-step, i-1
Q_{tot} = Target ventilation rate from ASHRAE 62.2-2016, L/s
Q_i = Ventilation rate from the current time-step, L/s
Δt = Simulation time-step, 300 (seconds)
V_{space} = Volume of the space, L

In time steps where there is no ventilation airflow, Relative exposure is calculated using Equation 3.

$$\boldsymbol{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \quad (3)$$

The relative exposure provides a snapshot of the ventilation rates at an instant in time. Some of our control strategies (e.g., Occupancy SVC and Lockout TSVC) attempt to maintain the daily average exposure equal to one. To do so, we define the *relative dose* as the 24-hour integrated relative exposure. Relative dose is calculated using Equation 4.

$$\boldsymbol{d_i = r_i * \left(1 - e^{\frac{\Delta t_c}{24}}\right) + d_{i-1} * e^{\frac{\Delta t_c}{24}}} \quad (4)$$

d_i = relative dose at time-step i
d_{i-1} = relative dose at the previous time-step i
r_i = relative exposure at time-step i
Δt_c = controller time-step, 5 / 60 (hr)

We report two different relative exposure values in this study, and they differ only in terms of which house airflow estimate they use. First, is the *controller relative exposure*, calculated using the airflow estimate available to the house's ventilation control system. This is the best information that a real controller could use to estimate exposure and control a ventilation fan. Second is the *real relative exposure*, calculated using the total airflow for the home that includes natural infiltration through envelop leaks. For this simulation study, we predict the actual house airflows using the CONTAM mass balance model described in Section 4.4.

At each time-step, *i*, the smart controller estimates the whole house combined mechanical and natural airflow to use in relative exposure calculations detailed above. Sizing of mechanical IAQ fans is detailed in Appendix R, where we also describe the biases in ASHRAE 62.2-2016 fan sizing and airflow estimates that lead the baseline cases to be marginally under-ventilated. This estimate always includes mechanical and natural infiltration airflows, and it may also include auxiliary fan airflows (e.g., bath and kitchen exhaust) depending on the control type. The airflow is estimated as outlined in the ASHRAE 62.2-2016 smaller time-step method of compliance. Infiltration ($Q_{inf,i}$) and mechanical fan airflows ($Q_{fan,i}$) are combined using:

$$\boldsymbol{Q_i = Q_{fan,i} + \emptyset\, Q_{inf,i}} \tag{5}$$

The sub-additivity coefficient, Φ, is calculated as follows:

$$\emptyset = \frac{\boldsymbol{Q_{inf,i}}}{\boldsymbol{Q_{inf,i}+Q_{fan,i}}} \text{ For unbalanced fans, and 1 for balanced fans} \tag{6}$$

When auxiliary fans are included in the whole house controller airflow estimate, they are added directly to the main IAQ fan airflow and included in the $Q_{fan,i}$ term. When the main IAQ fan is a balanced fan (and the auxiliary fans are unbalanced), the sub-additivity coefficient is calculated using only the auxiliary mechanical airflows included in the $Q_{fan,i}$ term when calculating Φ, and all the mechanical flows are used in $Q_{fan,i}$ when calculating Q_i.

The natural infiltration rate (Q_{inf}) used in estimating whole house airflow is determined using two separate methods allowed in the ASHRAE 62.2-2016 standard. First, is use of a fixed value for all hours of the year that reflects the annual effective infiltration for a given climate zone and home. For annual effective infiltration, we converted the envelope leakage from Air Changes per Hour at 50Pa (ACH_{50}, the metric most commonly used to specify air leakage in energy standards)

to Normalized Leakage (NL) and calculated the annual effective infiltration airflow using:

$$\boldsymbol{Q_{inf}} = \frac{\boldsymbol{NL(wsf)A_{floor}}}{\mathbf{1.44}} \quad (7)$$

where:
Q_{inf} = annual mean effective infiltration airflow, L/s
NL = normalized leakage, derived from blower door testing;
wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone;
A_{floor} = floor area of residence, m^2;

Time-varying infiltration estimates are also allowed by the ASHRAE Standard, using a simplified version of the enhanced infiltration model in the ASHRAE Handbook of Fundamentals, also known as the AIM-2 model (I. S. Walker & Wilson, 1998). The AIM-2 calculation procedure is described in detail in Appendix J and is aligned exactly with the procedures in ASHRAE 62.2-2016.

These relative dose and exposure calculations are used to determine when the fan being controlled is turned on or off in such a way as to achieve equivalent exposure over a year of operation. The fan on/off decision is made once every 5-minutes, which aligns with the overall simulation time step of 5-minutes. The SVC strategies analyzed in this work also turn the ventilation fan on or off in response to one or more of three different signals: outdoor temperature, occupancy, and auxiliary fan operation. In response to these signals, a ventilation fan is modulated to provide more ventilation when advantageous and less when not. The relative dose and exposure are tracked at all times – whether the ventilation fan is running or not.

To determine the energy savings from different smart ventilation strategies, we first determined the energy used to condition the ventilation air that was added by installing a continuous fan sized to the ASHRAE 62.2-2016 standard (see sizing method in Appendix R). This was done by simulating homes with no mechanical ventilation, and then simulating the same house with constant mechanical ventilation. Simulations were performed using EnergyPlus version 8.3.0, as described in Section 4.3. The difference in energy use is the baseline energy use for code-compliant mechanical ventilation in the homes. We then compare the energy used in different smart ventilation scenarios to determine their energy savings. These energy estimates include fan energy, as well as space conditioning energy required to treat the incoming air due to mechanical ventilation and natural infiltration. As such, there is some dependence in these estimates on the type and efficiency of the equipment specified for heating and cooling (see specs in Section 4.1).

3 Smart Control Descriptions

3.1 Temperature Controls

The energy impact of mechanical ventilation is primarily due to the changes in space conditioning loads, and to a much lesser degree, direct fan energy use. The load introduced or removed by ventilation airflow is proportional to the indoor – outdoor temperature difference, adjusted for air density and specific heat capacities. Therefore, we examined control strategies based on outdoor temperature signals.

While an infinite number of strategies based on this signal could be devised, we focused on five outdoor temperature-based smart ventilation control strategies (TSVC) that require only on/off fan control. For convenience we named these Lockout, Cutoff, MedRE, Seasonal and VarRE, which are arranged in order of increasing complexity. We also looked at one strategy that would require a continuously variable fan drive (VarQ). We describe each strategy briefly in the following sections, and we provide more detail, as needed, in Appendix A through Appendix H.

Most of the TSVC described in the following sections function seasonally, which means they require of estimate of when they are in Heating or Cooling modes. For example, the lockout controller described in Section 3.1.1 needs to determine whether it should turn the ventilation fan off during the hottest or the coldest hours of the day. It makes this determination using the Season indicator. Our season indicator follows the same definition that the CEC uses in its energy analysis to determine heating and cooling seasons. A 7-day running average outdoor dry-bulb temperature is calculated, and it is "Heating" if the running average is <60°F and is otherwise "Cooling".

Finally, in order to time-shift ventilation while maintaining equivalence with the target airflow from ASHRAE 62.2, the IAQ fan airflow must be increased above that used for the continuous fan baseline simulation. All smart control cases use over-sized fans, with most doubling the fan airflow from the matching baseline case. These Fan Size Multipliers (FSM) are described in greater detail in Appendix R.

3.1.1 Lock-Out (Lockout)

A lockout TSVC strategy is a timer-based strategy that controls ventilation based on the relatively predictable diurnal variation in outside dry bulb temperature. Using pre-calculated estimates of best timer strategies and required fan size, a smart controller turns the ventilation fan off during the hottest or coldest hours of the day (depending on season). The ventilation airflow is increased during all other hours of the day to ensure equivalence with a continuous fan. This strategy is simple and requires no sensors or internet communication: only a timer. The specification of this control type is described in greater detail in Appendix A.

For our analysis, the lockout period (coldest vs. hottest hours) was selected each day based on the CEC definition of heating and cooling seasons. To calculate the best hours to turn the ventilation fan off, we used all 16 CBECC weather files for the representative California locations. For each month of the year (1:12), an average outside temperature was calculated for each hour of the day (0:23), resulting in 288 values (12*24). This was done for each of 16 climate zones. We then sorted the hourly average temperatures for each month from lowest and highest, and we categorized the lowest and highest hours for every month and climate zone. The hours that occurred most frequently in the low and high categories were selected for the lockouts in Table 1.

Time Period	***Coldest Hours***	***Hottest Hours***
4-Hour	03:00 – 07:00	13:00 – 17:00
6-Hour	02:00 – 08:00	12:00 – 18:00
8-Hour	00:00 – 08:00	11:00 – 19:00

Table 1 Coldest and hottest 4-, 6- and 8-hour periods in each day. Used in TSVC lockout strategy.

As an example of control operation, Figure 1 shows the relative exposure, relative dose and outside temperature for a temperature lockout strategy. The lockout period is highlighted in pink. As expected, the relative exposure climbs quickly during the lockout period, up to peak around 1.8 (1.8 times the average of a constant-ventilation scenario). Then the over-sized ventilation fan operates continuously during all other hours, bringing the relative exposure down to roughly 0.7 and the relative dose (integrated exposure normalized to constant-ventilation strategy) to roughly 0.97, which reflects the integrated exposure over the prior 24-hours.

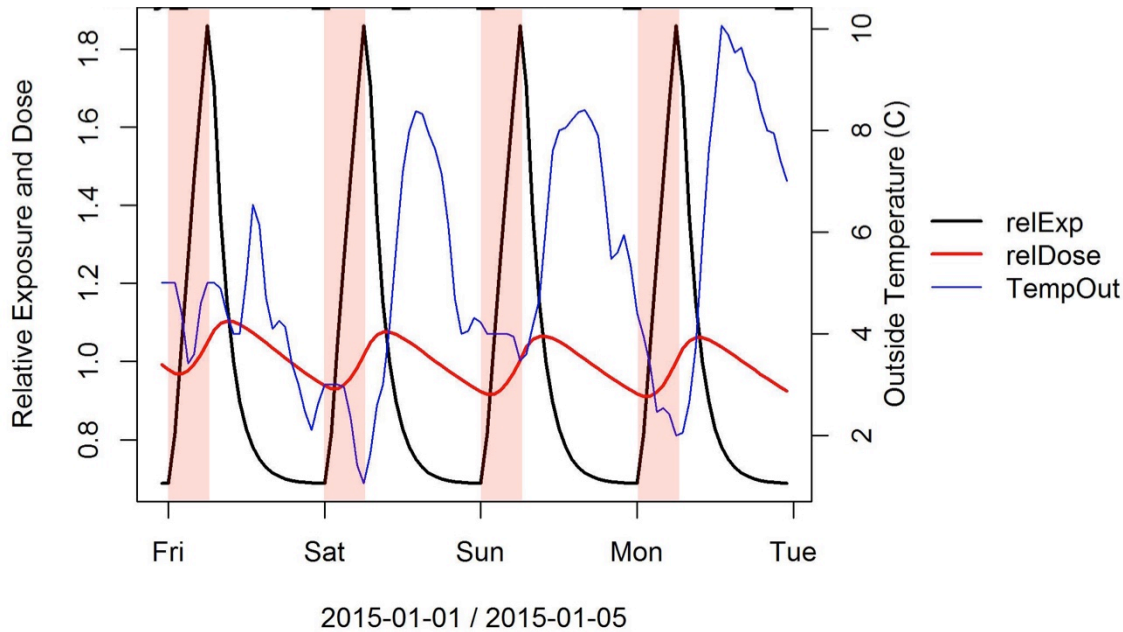


Figure 1 Illustration of the lockout control in 2-story, 1 ACH_{50} home in CZ1. Six-hour lockout period highlighted in pink.

3.1.2 Running Median (MedRe)

This smart control targets custom high and low relative exposure values based on comparing the current outside temperature (T_i) to its running median value ($T_{rollmedian}$). When in heating season, if T_i is currently colder than the running median, the ventilation is reduced (target RE_{high}), otherwise it is increased (target RE_{low}). Vice versa in the cooling season. Appendix B describes the process for selecting these exposure targets.

An illustrative example of this controller is shown in the time series plot in Figure 2, with the relative exposure, dose and outside temperature shown for a week in January. The high exposure target of 1.4 is maintained when the outdoor temperature is below the running median temperature, and when the temperature warms above the running median, the ventilation rate is increased and the exposure is driven down towards the low exposure target of 0.6.

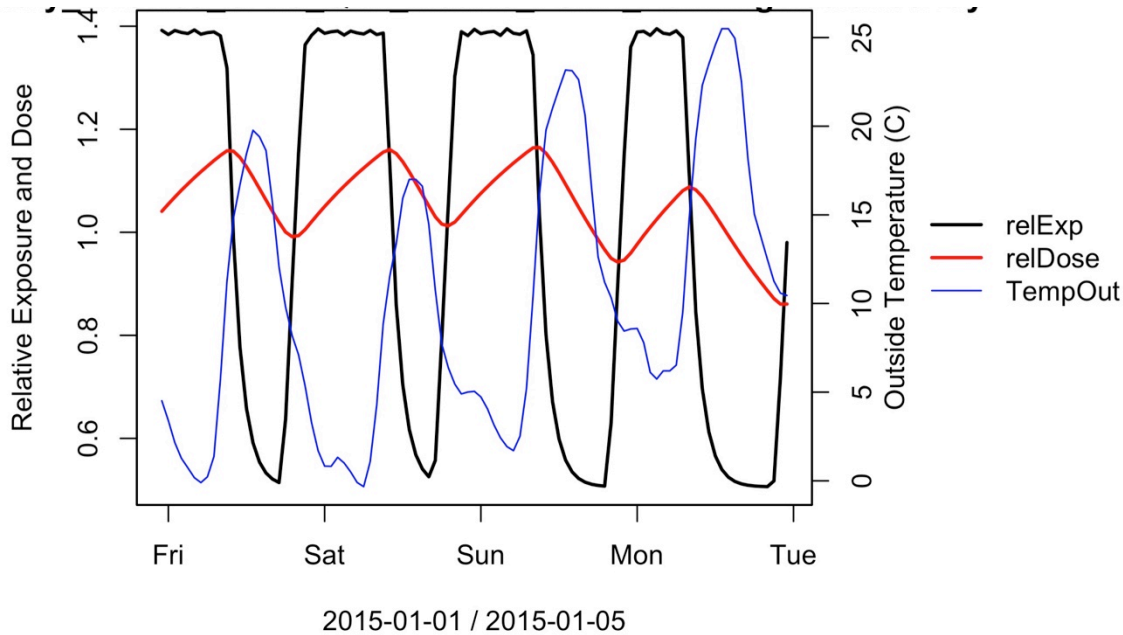


Figure 2 Example of the Running Median TSVC controller. 1-story medium, 3 ACH_{50} home in CZ10 with an FSM of 2. High RE target of 1.4 and low target of 0.5.

3.1.3 Seasonal Control (Season)

The Seasonal ventilation controller targets higher average exposure during heating season (reduced ventilation rate) and lower exposure during cooling season (higher ventilation rates), while maintaining annual relative exposure below one

High and low exposure targets can be calculated for any climate zone using a weighted average approach that provides an annual average very close to one. Again, the process for selection of these control points is not straightforward and we explain it in detail in Appendix C.

We illustrate the simple and consistent operation of this TSVC using daily minimum, mean and maximum controller exposure values in Figure 3. This example case is a 1-story medium 5 ACH_{50} prototype in CZ10, with a heating season exposure target of 1.5 and cooling season target of 0.61. When in heating season, the 1.5 target is consistently maintained, with very little variability over the course of a day; same for the cooling season at the low exposure target. This predictable behavior ensures relatively straightforward estimation of the annual average exposure during design phase.

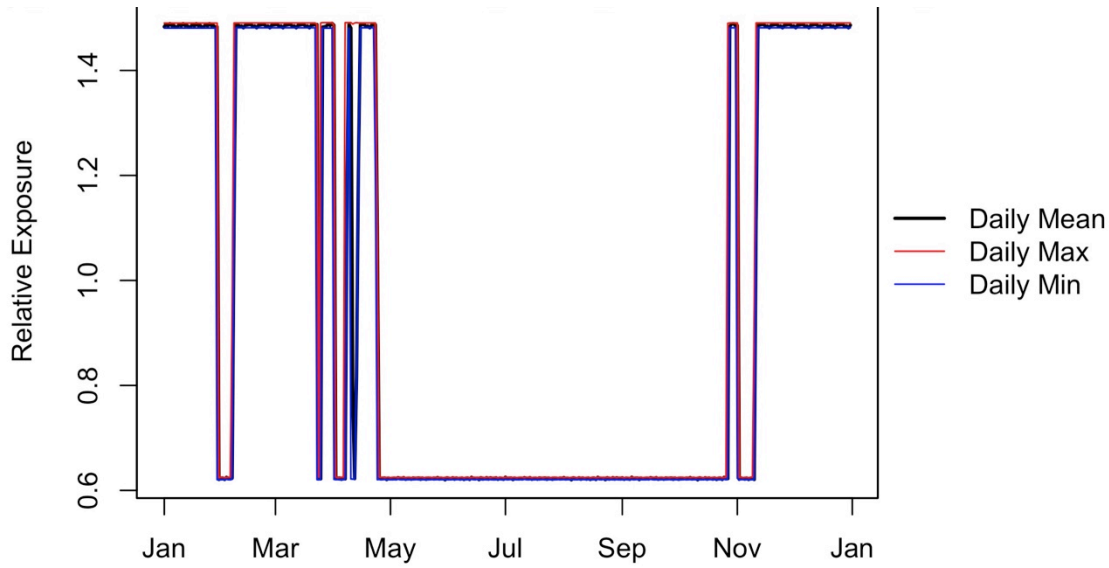


Figure 3 Seasonal TSVC illustration of daily minimum, mean and maximum values for controller relative exposure. 1-story medium 5 ACH50 homes in CZ10 with heating season RE target of 1.5 and cooling season target 0.61.

3.1.4 Cut-Off Temperature Control (CutOff)

It may be possible to achieve greater energy savings if an additional level of complexity is added onto the Seasonal control. Past work on temperature-controlled smart ventilation suggested that a simple cut-off temperature was an effective approach to reducing ventilation load through smart control (Less et al., 2014). In this work, we developed a cut-off approach that ensures annual relative exposure less than one using a weighted average approach. This approach uses two cut-off temperatures: one for each season (heating and cooling). We found that it was not practical to simply turn a ventilation fan on or off when outdoor temperature crossed these temperature thresholds. Instead, we elected to change the target value of relative exposure when the outdoor temperature crosses the temperature threshold.

For example, in the winter, when outdoor temperatures are relatively warm (above the cut-off temperature), the lowest relative exposure would be targeted (increasing ventilation rates). When outdoor temperature is low (below the cut-off temperature), a higher exposure would be targeted (reducing ventilation rates). The high and low exposure targets are selected for each season, so that the seasonal exposure averages equal those used in the Seasonal controller. Figure 4 illustrates such a control strategy with the cut-off temperature shown as a dashed green line. When the outdoor temperature rises above the cut-off, the ventilation rate is increased and a low exposure is targeted; otherwise the high target of roughly 1.8 is maintained. The process for choosing temperature cutoff thresholds and RE targets is explained in depth in Appendix D.

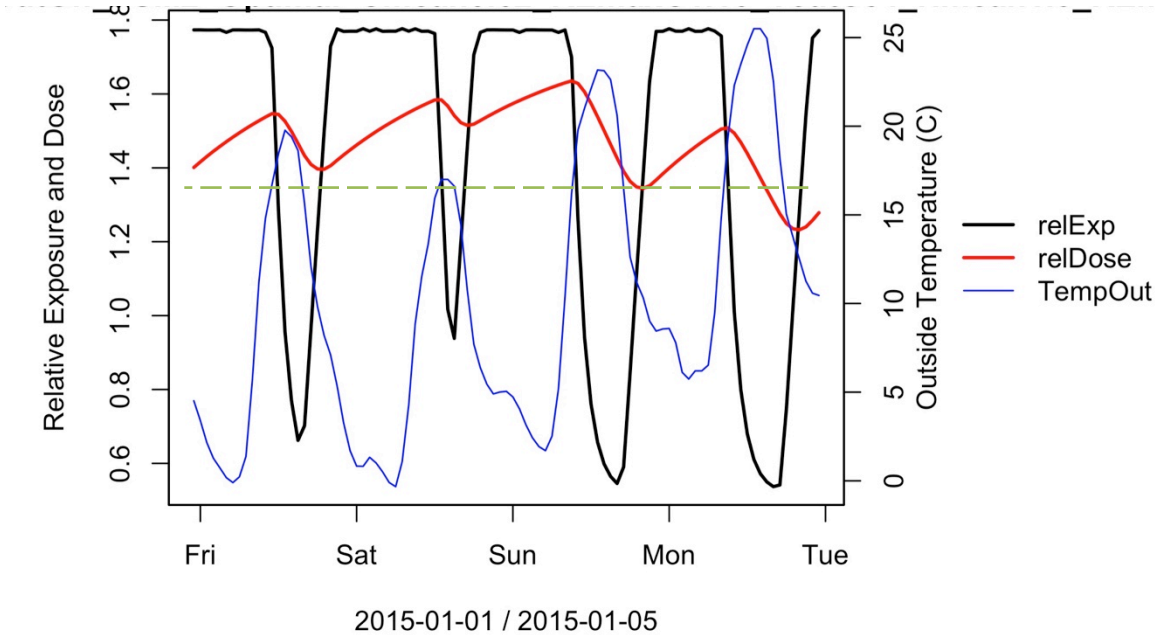


Figure 4 Time-series illustration of Cutoff TSVC controller exposure, dose and outside temperature in a 1-story 1 ACH_{50} home in CZ10. Low exposure target (high ventilation rate) is targeted when outside temperature (blue line) exceeds 16.7°C (dashed green line).

3.1.5 Optimized Variable Relative Exposure (VarRe)

Another level of complexity can be added to try and extract more energy savings by targeting not just high and low exposure values, but instead to make the exposure target a continuous function of outdoor temperature. We propose a method for continuously calculating this optimized relationship target throughout the course of a year while maintaining equivalence with the ASHRAE ventilation standard in Appendix F.

An example VarRe control is plotted across a range of outside temperatures in Figure 5, showing the relative exposure target at each outside temperature. Recall that higher exposure values mean reduced ventilation rates. The RE_{max} values are different in heating (4.0) and cooling seasons (2.0), the RE targets scale linearly between the thermostat setting and the annual minimum temperature in heating (or maximum temperature in cooling season). When outside air is above the thermostat setting in the heating season, ventilation is increased to its maximum to get free heating (RE target of 0.5), vice versa in cooling season.

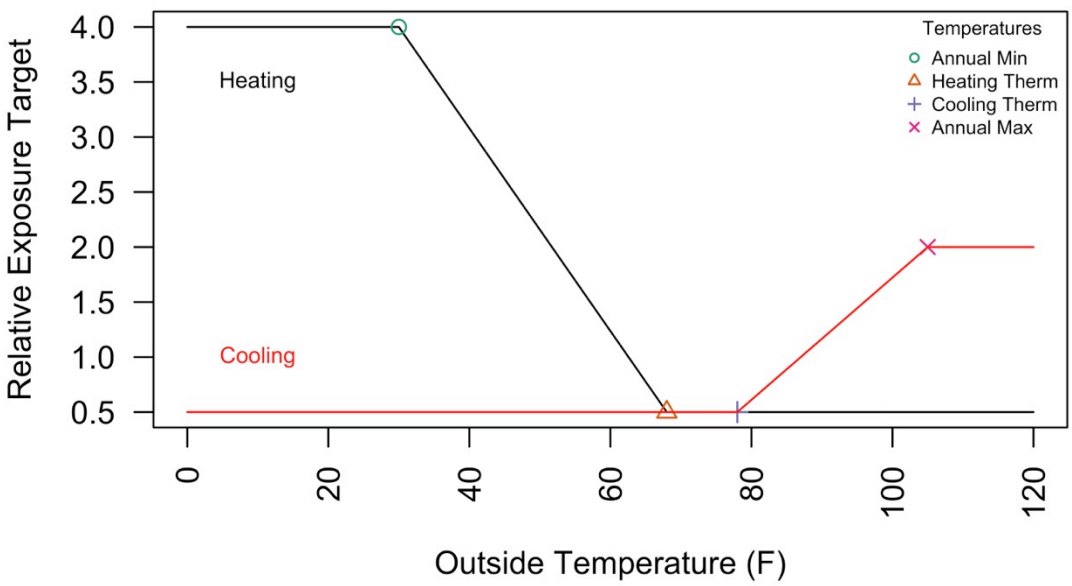


Figure 5 Relative exposure targets that vary continuously with outside temperature, using an RE_{max} values optimized independently for heating and cooling seasons.

The VarRe TSVC strategy is illustrated by the time-series plot in Figure 6 showing a 1-story 1 ACH_{50} home in CZ10 with a peak heating season exposure target of 4.1 (unusually high). We see that the exposure values (real and controller) are inversely proportional to the outside temperature, with peak exposure occurring at the lowest temperature (around 0°C). The controller functions as intended, to shift almost all house ventilation to warmer periods of the day and year (in heating season).

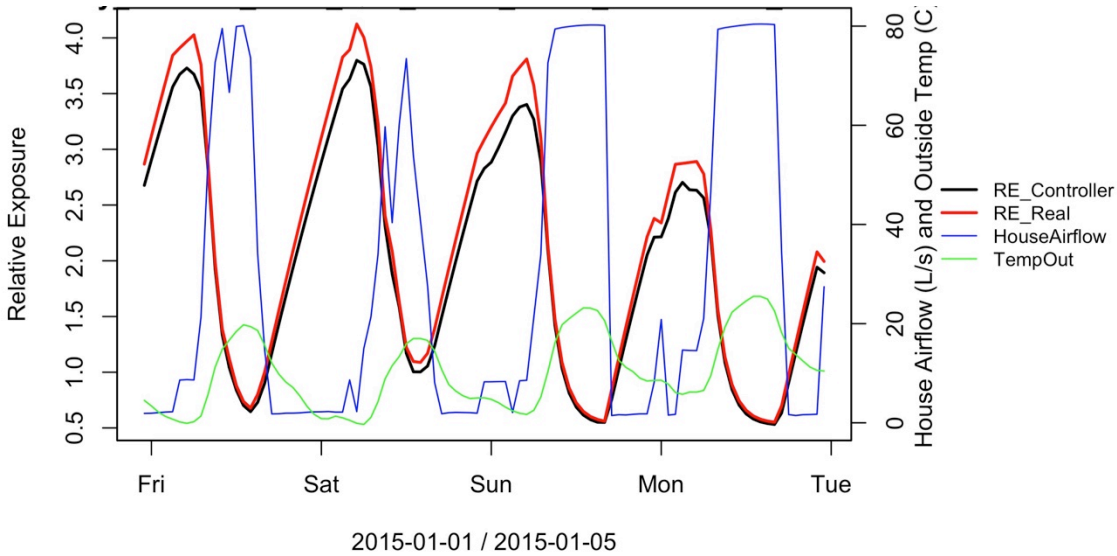


Figure 6 Time-series illustration of the VarRe TSVC controller in a 1-story 1 ACH_{50} home CZ10 (Riverside), with a fan size multiplier of 2 and a peak heating exposure target of 4.1. Includes real and controller exposure, along with whole house airflow and outside temperature.

3.1.6 Optimized Variable Airflow (VarQ)

In homes equipped with variable speed fan drives, continuous modulation of fan speed and thus ventilation rate in response to outdoor temperature signals will be possible. We called this type of strategy VarQ. This scales the target fan airflow between 0 (off) and maximum in response to outdoor temperature signals, exactly as the VarRe controller scales the exposure target with temperature. We illustrate an example strategy across a range of outside temperatures in Figure 7. The heating season airflow (black line) is set to 0 when outside temperature is below the T_{max} value (roughly 45°F here), it scales fan airflow linearly up to the maximum airflow when outside air is the same as the thermostat setting (65°F), and the fan airflow remains at maximum at all temperatures warmer than the thermostat setting (free heating). The opposite happens in cooling season (see the red line). The choice of maximum and minimum temperature control points is based on parametric optimization and is explained in Appendix E.

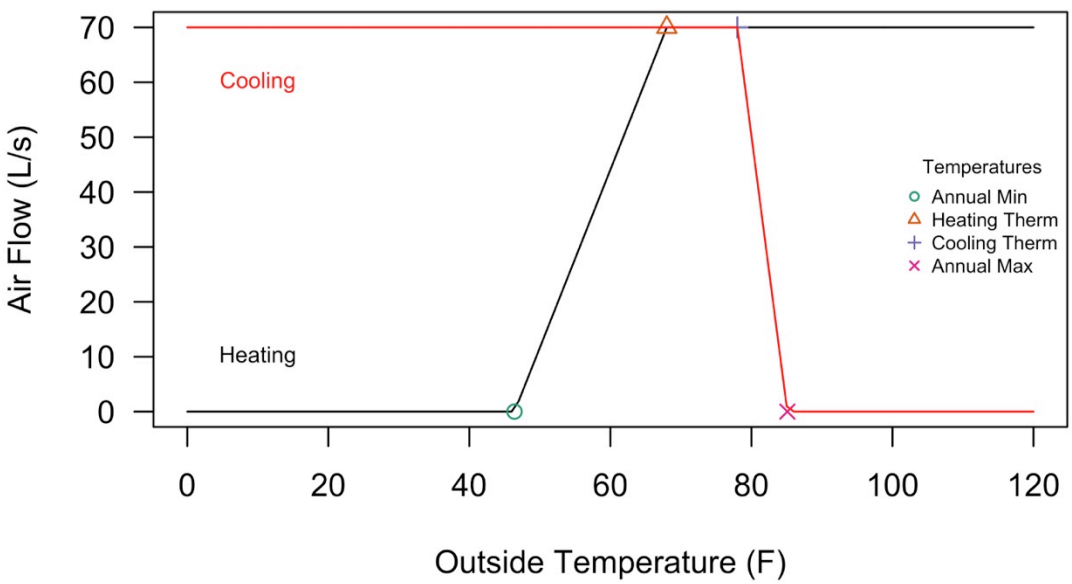


Figure 7 Example airflows for a 70 L/s smart ventilation fan in heating (black) and cooling (red) seasons, generated using F-scale factor across range of outside temperatures.

A time-series illustration of this VarQ controller is plotted in Figure 8 for a 1-story 5 ACH_{50} home CZ10 (Riverside) with a fan size multiplier of 2. This plot shows the real and controller estimates of relative exposure, along with the house airflow and outside temperature. The real exposure is higher than controller exposure due to having lower air exchange. This is due to differences in calculating the natural infiltration between the real and controller approaches. We see that for most hours of the day, the VarQ controller keeps the house airflow at a low number, essentially equal to the natural infiltration rate. When the outside temperature increases, the IAQ fan airflow ramps up proportionally until it is at full airflow around 80 L/s at any temperature exceeding the thermostat set point.

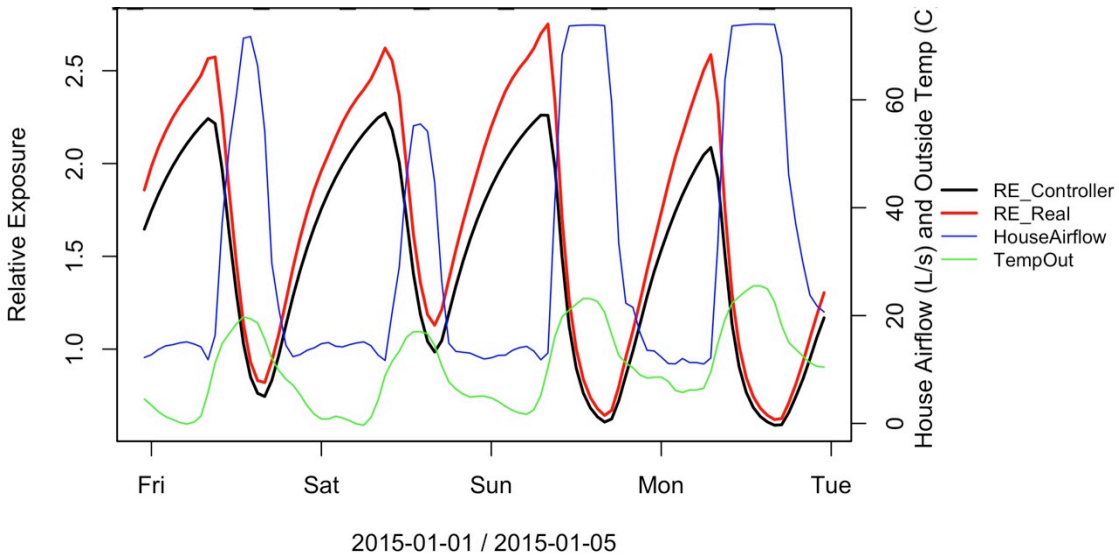


Figure 8 Time-series illustration of the VarQ controller in a 1-story 5 ACH_{50} home in CZ10 (Riverside), including controller and real exposure, along with house airflow and outside temperature.

3.2 Occupancy Controls

In addition to or instead of temperature, SVC strategies may also respond to occupancy signals and reduce ventilation during unoccupied periods. Occupancy-based smart ventilation control (OSVC) is distinguished from many other demand-controlled devices, which have historically used either relative humidity or CO_2 as indicators (Emmerich & Persily, 2001; Fisk & De Almeida, 1998; Raatschen, 1990). This approach assumes that occupancy is directly detected by any variety of methods, which could include IR motion sensors, smart phone network detection, smart meter analytics, simple timer-based scheduling, etc. Unlike the temperature-based controls described in the prior section, the occupancy controller is intended to save energy by reducing the average ventilation rate of the home, while maintaining exposure less than one during occupied times.

In this work, we assess the performance of three versions of OSVC: (1) ventilation off during unoccupied periods ("Unocc"), (2) fan on low speed during unoccupied periods (Reduc), and (3) a version that flushes the house at a high ventilation rate one hour before occupancy (Flush). These are described in more detail presently. See Appendix G for more details on Occupancy SVC.

3.2.1 Off while unoccupied (Unocc)

During the unoccupied period, the ventilation fan is turned off, while the relative exposure is continually calculated. If at any point during the unoccupied period a maximum exposure of 5 is exceeded, the ventilation is turned on to maintain this maximum value. This is a requirement of ASHRAE 62.2-2016. This maximum relative exposure is based on the acute to chronic concentration ratios for pollutants of concern. More details are available in M. H. Sherman, Logue, & Singer (2011) and Max H. Sherman et al. (2012). In most homes, this means the IAQ fan is turned off

during the entire unoccupied time period, because the occupants are not exposed to the contaminants in the space and exposure never reaches 5. This is acceptable, as long as the controller accounts for the increased exposure the occupants receive when returning home after the ventilation system had been off. To account for this, our Unocc control increases the ventilation rate immediately after occupants return home, and it operates at this higher level until the daily-integrated pollutant exposure is equivalent to a continuous fan.

An illustration of the Unocc SVC is provided in Figure 9. The day begins with the IAQ fan maintaining relative exposure (*relExp*, red line) near 1. Light grey highlighted periods show IAQ fan "on" periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home reflecting their exposure to this high concentration, and it is reduced back below one during the recovery period when the ventilation rate is increased. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

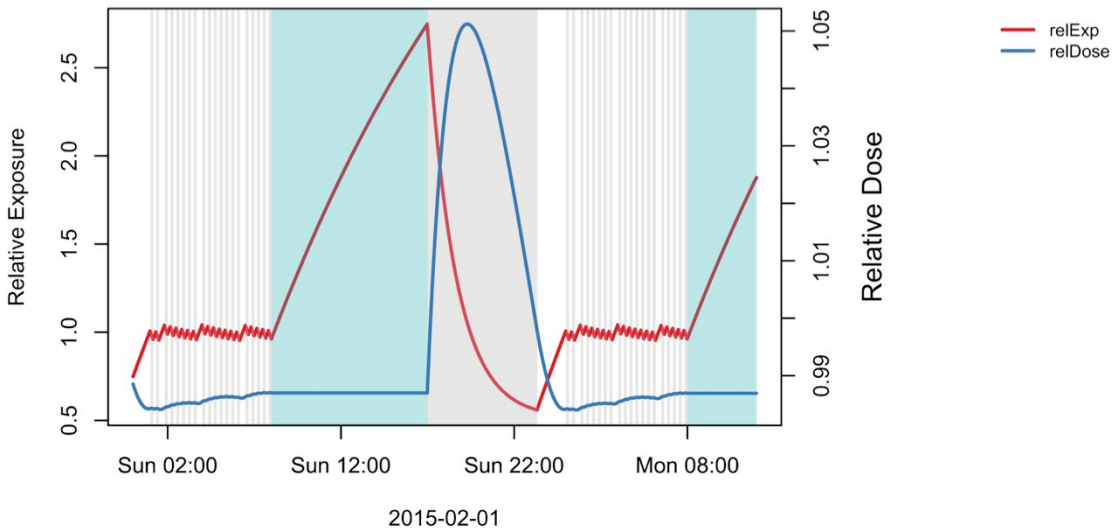


Figure 9 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

3.2.2 Ventilation reduced while unoccupied (Reduc)

Rather than turning the fan off during unoccupied periods, it may prove advantageous to operate it at a low airflow instead. Mortensen, Walker, & Sherman (2011) showed that for a variety of unoccupied periods, emission assumptions and constant fan airflows, the peak effectiveness of an-occupancy controlled system

occurred when the ventilation rate during unoccupied times was between 0.13 and 0.4 of the constant system. Their results suggest that a value of roughly 0.35 will be appropriate for the cases we are simulating. So, we analyzed a strategy that operated the continuous fan airflow at 0.35 times the baseline rate during unoccupied time periods. It was expected that this approach would reduce the peak exposure experienced everyday by the occupants, and hopefully reduce the average ventilation rate required to maintain exposure below one, thus saving energy.

3.2.3 Pre-occupancy flush out (Flush)

We also tested a version of the occupancy SVC where the controller can predict when occupants will return home. In these example cases, the controller begins the over-ventilation recovery period before occupants return home. We have reproduced a figure from Less & Walker (2017) demonstrating typical relative exposure patterns in an occupancy controller with no pre-venting, 1- and 2-hour pre-occupancy flush outs in Figure 10.

This shows how the flush outs drastically reduce peak exposure to the occupants and lessen the over-ventilation period. For example, in the 9-hour absence pattern detailed in Figure 10 the occupants return home at 17:00, and this controller would turn the fan on continuously starting at 15:00 for a 2-hour flush out or 16:00 for the 1-hour flush out. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. Less & Walker found that 1- and 2-hour flush outs had very similar energy performance, so we only test a 1-hour flush out in this work.

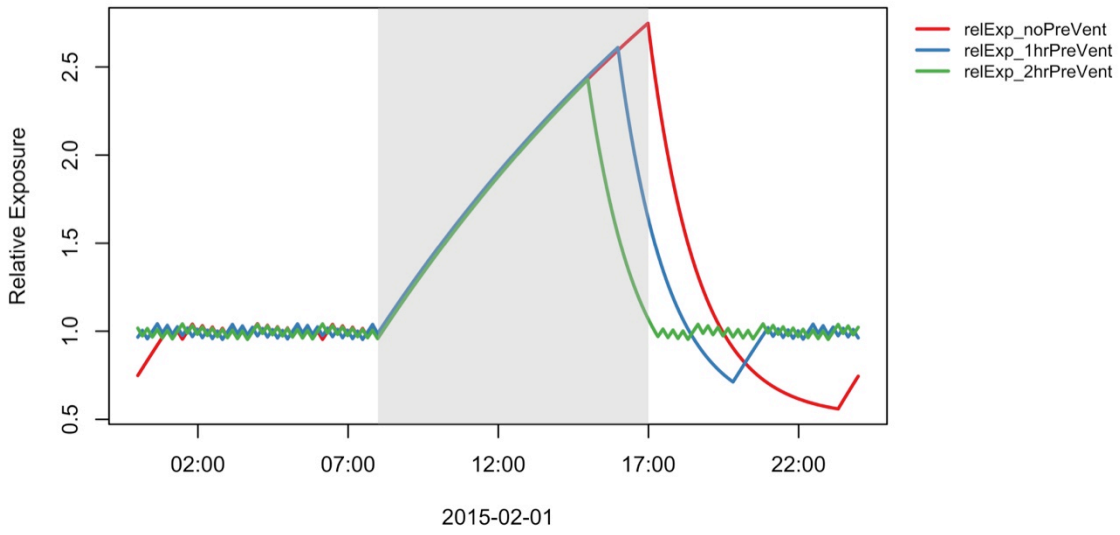


Figure 10 Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey. Reproduced from Less & Walker (2017).

The risk with the pre-occupancy flush out strategy is that it may be more difficult for a controller to predict when occupants will return home than it is to sense that they

have returned home. The prediction requires a predictable pattern, whereas the simple approach with no flushing period requires only an accurate sensor (the low airflow during unoccupied times might also be more flexible in response to variable occupancy patterns). In addition, this only works for typical workweek schedules, with predictable home and away periods. Luckily, Less & Walker (2017) showed that a one-hour flush out was roughly equivalent in energy performance as the two-hour flush out, which gives the controller flexibility.

A simple approach to predicting when occupants will return would be a running average of the prior five work day return times. The system could also work on a schedule that is manually entered by the occupants that reflects their typical home and away patterns. Alternatively, a system could be used that is integrated with an occupant's cell phone that informs the controller when the occupants are within a certain radius of their home or some such approach.

3.3 Auxiliary Fan Controls

A smart control strategy may be augmented by detection of other exhaust devices in the home, including bathroom, kitchen and laundry fans, vented clothes dryers and economizers. These additional airflows can be added by the controller to the ventilation rate used in calculating relative exposure and dose. The central fan's operation can be traded off on a one-to-one basis with auxiliary fans, reducing the overall ventilation rate. This is distinct from controls that time-shift ventilation (i.e., temperature-based controls), because they have to increase the average ventilation rate in order to maintain exposure less than one, whereas this control reduces the average ventilation rate. The benefits of this type of control scale directly with the amount of auxiliary fan use and airflow. More details are provided about auxiliary fan sensing in Appendix H.

3.4 Combined Controls

Less & Walker (2017) have already demonstrated that combining an occupancy controller with auxiliary fan sensing greatly improved the overall performance. We extended this further to include occupancy controls with pre-occupancy flush out and a low airflow fan operation during unoccupied periods. We also add auxiliary fan sensing to each of the previously described temperature-based smart controls. A combination of all three control inputs may be possible, but was not explored in this work.

3.5 Smart Controls Overview

For the reader's convenience, all smart controls described above and in the Appendices are listed and briefly summarized in Table 2.

Control Name	***Description***
Lockout	Turns IAQ fan off during the hottest hours of the day in the cooling season and during the coldest hours of the day in the heating season. Lockout hours (4-, 6- and 8-hours) are pre-calculated using weather files. Fans are oversized to run continuously outside of lockout hours to ensure daily exposure ≤0.97. See Appendix A.
Running Median (MedRe)	Compares current outside temperature against the running median outside temperature, and selects either a high exposure target (reduced airflow) or a low exposure target (increased airflow). During heating season, ventilation is reduced when below the median and increased when above the median. Opposite in cooling season. See Appendix B.
Seasonal (Season)	Reduces ventilation rates in the heating season and increases them in the cooling season. Exposure targets for each season are pre-calculated using a weighted average to ensure that annual exposure will be ≤0.97. See Appendix C.
Cutoff	Uses the exposure targets from the Seasonal controller, and adds cut-off temperatures for each season selected by parametric optimization, with a low and high exposure target. Reduces ventilation during the heating season, with a focus on the coldest hours, while still ventilating at high rates during mild weather. Vice versa in cooling season. See Appendix D.
Variable Airflow (VarQ)	Ventilation fan airflow is continuously varied proportional to outdoor temperature. Airflow is scaled using the ratio of the current indoor-outdoor temperature difference, compared with the seasonal maximum temperature difference. The seasonal maximum values are selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97. See Appendix E.
Variable Exposure (VarRe)	Target exposure is continuously varied proportional to outside temperature. Exposure varies between the minimum value (highest airflow) and a maximum value (lowest airflow) for each season. High exposure target is selected using parametric optimization to ensure maximum energy savings, with annual exposure ≤0.97. See Appendix F.
Occupancy (Occ)	IAQ fan is turned off when the home is unoccupied, and ventilation rate is increased when occupants return home to account for background contaminant emissions. Daily-integrated exposure is maintained ≤0.97. See Appendix G. Three versions are assessed: • Fan off when unoccupied • Fan at 35% flow when unoccupied • Pre-ventilate the home 1-hour before occupancy
Auxiliary Fans (AuxFans)	This option senses the operation of other exhaust devices in the home, and it includes these flows in the controller airflow estimate, which reduces IAQ fan runtime and overall ventilation rates. This controller was added onto each of the other control types to assess combined control performance. See Appendix H.

Table 2 Description of each smart control strategy.

4 Modeling and Analysis Methods

In order to study the energy and indoor air quality (IAQ) benefits and consequences of smart ventilation strategies, we first created a combined energy-IAQ model of two representative California home types, in several different California climates. We then analyzed the performance of these homes with respect to both energy and IAQ under a variety of different smart ventilation control strategies.

The following sections describe the models used in the simulation program and the specifics of the simulation protocol. In general, we followed the following procedure in this study:

1) Develop CONTAM models to assess the IAQ portion of the problem for each of 6 representative homes: three different air-tightness levels for each of the two prototype homes.

2) Develop EnergyPlus models to assess the thermal and systems portion of the problem for each of two homes

3) Co-simulate EnergyPlus and CONTAM models across the homes, climates and control strategies of interest via an automated parametric modeling approach.

4) Process the outputs.

Each of these portions of the simulation work is described below.

All energy assessments included both site energy and time dependent valuation (TDV) energy, which is a metric used in demonstrating Title 24 compliance that accounts for time-varying impacts of energy consumption. Our TDV methods are described in Appendix Q TDV energy weights peak demand periods heavily for electricity consumption, so it partly reflects peak demand reductions. We also performed a specific peak period analysis that is described in Appendix P to analyze the potential grid services provided by the controllers. We present detailed results across climate zones and house types where possible, but we also use a weighted average calculation method to generalize our results across new homes constructed in the state (see a complete description in Appendix N).

4.1 Homes simulated

We simulated homes matching the specifications of the two CEC single-family prototype units (Nittler & Wilcox, 2006), whose properties are made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. We created detailed models of two prototype homes: a 1-story 2,100 ft^2 prototype home and a 2-story 2,700 ft^2 prototype home, with forced air space conditioning systems. The HVAC was sized using ACCA Manual J load

calculation procedures (see HVAC system parameters in Table 4), with thermostat schedules were set to meet those specified in the 2016 ACM. The systems are compliant with ASHRAE 62.2-2016 that includes with infiltration credits and sub-additivity adjustment (see sizing calculations in Appendix R)[2].

Several deliberate deviations were made from the Title 24 prescriptive path prototypes; we included whole house economizer fans that are not present in the prototype homes; we improved the HVAC equipment efficiencies. We did not model any duct leakage because we modeled advanced homes with ducting assumed to be within conditioned space, consistent with Title-24 2016 prescriptive path option C. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice encountered in HENGH field study and based on TAC feedback. Figure 2 shows the front view of the two prototype homes. The specific model input values for the two prototypes are summarized in Table 3.

[2] This fan sizing is not the same as that adopted in the 2019 Title 24 building energy code cycle. The newly adopted Title 24 fan sizing method uses the same calculation procedures as the ASHRAE 62.2-2016, but for all homes with envelope leakage 2 ACH_{50} and greater, a default of 2 ACH_{50} is used in fan sizing calculations. For homes that are below 2 ACH_{50}, the newly adopted fan sizing method requires use of the small leakage value in calculating the fan airflow. So, for homes ≤2 ACH_{50}, the methods are identical, and in leakier homes, the adopted sizing procedure leads to larger fan airflows than are required by ASHRAE 62.2-2016.

Figure 11 CEC one- and two-story homes (front view)

Element	*Prototype 1*	*Prototype 2*
Ceiling height (ft)	9	9
Conditioned Floor Area (ft^2)	2,100	2,700
Conditioned Volume (ft^3)	18,900	25,750
Gross Areas		
Slab (ft^2)	2,100	1,250
Slab perimeter, outside (ft^2)	162	128
Slab perimeter, garage (ft^2)	30	30
Ceiling (ft^2)	2,100, unvented attic	1,450, unvented attic
Roof slope (%)	20	20
Roof Deck R-value	R13 (airspace) below deck insulation, in CZ4 and 8-16	R13 (airspace) below deck insulation, in CZ4 and 8-16
Ceiling Insulation	R38 (R30 in CZ3, 5, 6 and 7)	R38 (R30 in CZ3, 5, 6 and 7)
Radiant Barrier	No	No
Wall U-value	0.051 (0.065 in CZ6&7)	0.051 (0.065 in CZ6&7)
Slab Perimeter R-value	0 (7 in CZ16)	0 (7 in CZ16)
Window U-value	0.32	0.32
Window SHGC	0.25	0.25
Window Area	20% floor area	20% floor area
Gas Furnace AFUE	92%	92%
AC SEER	16	16

Table 3. Model input values for prototype homes

CZ	Air Handler Fan Efficacy {W/cfm}	Air Handler Flow Rate (cfm)	Rated Total Cooling Capacity (W)	Rated Cooling COP (W/W)	Gas Heater Nominal Capacity {W}	Gas Burner Efficiency, AFUE
1	0.365	593	5275	3.95	7033	0.92
3	0.365	593	5275	3.95	7033	0.92
10	0.402	996	8792	3.95	7033	0.92
16	0.365	805	7034	3.95	7033	0.92

Table 4 HVAC system variables for each climate region.

4.2 Climates

Locations were first selected that represented a broad range of climatic conditions in California. It was important to capture the variety of heating, cooling and moisture regimes throughout the state, in order to allow statewide estimates that interpolate between the results in these limited locations. Table 5 gives the climatic design data for 4 representative cities, from the harshest Blue Canyon (CZ16) to the very temperate Oakland (CZ3), and Riverside (CZ10) in the central valley that represents a location with greatest growth in new construction.

CEC Climate Zone	$HDD_{18.3}$	$CDD_{18.3}$	Design Temperature (Heating – Cooling, °C)
1 – Arcata	2,658	1	0.6 / 20.6
3 – Oakland	1,436	85	2.2 / 26.7
10 – Riverside	1,011	888	1.7 / 37.2
16 – Blue Canyon	3,174	151	-4.4 / 27.2

Table 5 Climate zone design information, including heating and cooling degree days calculated at 18.3°C reference temperatures, and heating/cooling design temperatures.

EnergyPlus weather files (.epw) are available for each of these locations; however, these differ substantially from the CEC weather files (.csw) used to demonstrate Title 24 residential compliance. The team used data (dry-bulb temperature, dew-point temperature, wet-bulb temperature, wind direction, wind speed, global horizontal irradiance, direct normal irradiance, diffuse horizontal irradiance and total sky cover) from the CEC weather files, to generate corresponding .epw files. Where required, these values were converted from the IP system in the CEC .epw files to SI units for use in EnergyPlus. Relative humidity was derived using dry-bulb and wet-bulb temperatures from the CEC file with the paired atmospheric pressure in the original epw files.

4.3 Energy Model

For each home and climate, we modeled the thermal interaction of the building with its environment and internal loads with EnergyPlus (U.S. DOE, n.d.). EnergyPlus is a comprehensive building operation simulation tool supported by the Department of Energy (DOE), which has sophisticated models for building heat balance, HVAC operation, lighting, etc. The simulations were executed on a 5-minute time-step, with hourly time-series reporting.

EnergyPlus models for the two prototype homes were developed with BEopt, using detailed construction and HVAC system parameters described in Section 4.1. This determines the system capacities and their associated airflows. BEopt implements residential-specific models in EnergyPlus using a simple graphical user interface, including user-friendly specification of building geometry and performance features, along with residential defaults for internal heat gains, appliance and lighting usage, etc. After the baseline models were developed, we performed a series of verification exercises to ensure that the models adequately represented house airflows, indoor temperatures, HVAC system behavior, etc. In doing so we identified a number of issues and addressed them, described further in Appendix L Detailed HVAC system and indoor temperature operation.

Once we were satisfied with the dynamics reflected in the EnergyPlus models from BEopt, these were then modified to include the objects that handle the interactions with CONTAM via the FMI, and our EMS control code. The EMS code is used to calculate the:

- Total infiltration and inter-zonal mass exchange.
- Operating behavior of the HVAC system.
- Operation of the various smart ventilation control strategies.
- Fan power use.
- The whole house flow rates used by the smart controller, including infiltration, the IAQ fan, and when required by the control strategy, the auxiliary mechanical flows.
- Control and "real", exposure and dose.

These EMS programs influence the behavior of the model principally by setting values of commonly used EnergyPlus objects (schedules, infiltration flows etc.) using an EnergyPlus object called an *Actuator*. See the EnergyPlus references to learn more about that. Appendix I lists the main EMS programs and the actuators they control in more detail.

EnergyPlus fixes indoor temperatures at the thermostat set-points, with the HVAC system energy consumption modulated to meet that exact temperature. This does not account for the dynamics of indoor temperature that cycle up and down with HVAC system cycling, or float during temperatures of low load. This was very

important in our simulations because we are controlling ventilation on sub-hourly time steps and calculating the resulting changes in energy use. Getting house temperatures to adequately reflect real homes is critical when using temperature-based smart ventilation controls.

In order to get the models to reflect indoor temperature and HVAC system behavior in real homes, we imposed a thermostat dead-band of plus and minus one degree C. In the context of this HVAC system this means that the system will generally operate at full capacity before turning off. This addresses the issue of variable HVAC capacity that is the default behavior in EnergyPlus. This results in the house temperature cycling above and below the thermostat setting.

4.4 Airflow Model

EnergyPlus also has the capability to model multi-zone air flow and contaminant balances. However, its functionality for multi-zone airflow modeling is limited. EnergyPlus does not account for contaminant removal within the HVAC system loop, and is otherwise limited to CO_2 and a single generic contaminant. It is also limited in a few other ways: its ability to model the impact that HVAC system operation has on envelope infiltration is limited; implementing an EnergyPlus Air Flow Network model with HVAC distribution, is limited to a subset of air distribution systems and most importantly it cannot handle variable speed fans, which is critical for our smart control strategies.

CONTAM, in contrast, developed by National Institute of Standard and Technology (NIST) (Dols & Polidoro, 2015), cannot model building energy use, but has more sophisticated and flexible models for contaminant transport and loss. Using CONTAM, we are able to model contaminant loss mechanisms both in the zone and in the HVAC pathway itself. It also allows us to model multiple-contaminants or species of the same type of contaminant. These two features are essential requirements for the SVACH project, particularly for phase two of the study, where combinations of multiple pollutants are considered.

Thus, in order to understand the combined effect of wind- and buoyancy- driven infiltration, mechanical ventilation fan operation and envelope leakage, we built airflow models of each of the two prototype homes in CONTAM. The geometry, aspect ratio floor area and zone heights were also specified to match the EnergyPlus model. In total, we developed six different CONTAM files: three levels of air tightness for each of the two prototype home sizes; there is no variability in CONTAM models by climate zone. Each model effectively had two well-mixed thermal zones to match the corresponding EnergyPlus model:

1. The main conditioned living area which we were analyzing, and
2. The attic, which was used to appropriately treat the ceiling airflows and any HVAC system interactions with the attic (such as duct leakage).

The major advantage of the CONTAM simulation platform is that it has a detailed accounting of infiltration at each time step (5-minutes, in this work) via solution of pressure-flow relationships. This is described detail in Appendix K along with the assumptions we used for wind-driven ventilation and leakage area distribution.

4.5 Implementation of the EnergyPlus and CONTAM Co-simulation

To model the energy and IAQ implications of our various control strategies we used a co-simulation based approach, using CONTAM to perform mass and contaminant balances, and EnergyPlus to model energy consumption and implement smart ventilation controls and calculations.

Performing a co-simulation involves running the two simulation engines in parallel, with critical data connections passed back and forth at each time step, as shown in Figure 12. This allows us to take advantage of the relative strengths of each tool, and to meet all of the simulation objectives of the work, that no single tool could meet. Our method was based on an approach developed and validated by Dols et al. (Dols, Emmerich, & Polidoro, 2016), with a number of significant differences discussed later in this report. Dols et al. used a Functional Mockup Unit- (FMI, http://fmi-standard.org/) based implementation of CONTAM, which is then coupled to EnergyPlus via its FMI implementation (Thierry Nouidui, 2014) .

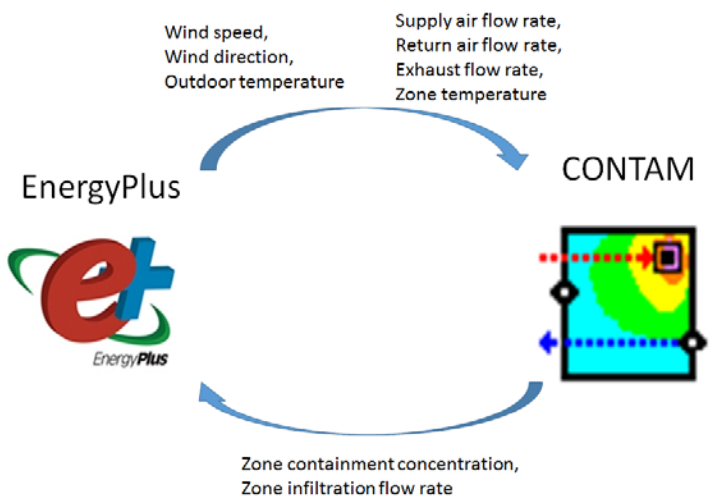


Figure 12 Co-simulation variable exchange diagram.

We used EnergyPlus to model the building envelope; HVAC system and controls; occupants and building energy use. CONTAM was used to model the air flow mass balance including inter-zonal air flow, mechanical air flow and infiltration, and contaminant transport. At each timestep, environmental data (wind speed, direction and outdoor temperature), and system operation data (mechanical system flows), are sent from EnergyPlus to CONTAM. Figure 12 illustrates this flow of information between CONTAM and EnergyPlus. The EnergyPlus Energy Management System (EMS) is used to manage this interchange and to implement required calculations and control strategies.

The IAQ fan and auxiliary fans flow rates are calculated in EnergyPlus using system operation schedules, defined in the EnergyPlus model file. Once transferred to CONTAM via the FMI, they are represented in CONTAM as “flow paths”. CONTAM then calculates the resultant infiltration and inter-zonal mass flows, considering these mechanical flows, along with wind driven and stack effects to determine the resultant mass flow rate. This infiltration is then returned to EnergyPlus to align the two models’ air change rates.

Once both the EnergyPlus and CONTAM models were defined the team used an approach based on prior work by NIST (Dols & Polidoro, 2015) to establish the co-simulation. NIST provides a publicly available tool (CONTAM 3D Export tool) that can be used to generate much of the necessary elements that are needed to perform co-simulation. These elements can be broadly categorized into 3 types. Firstly, additional EnergyPlus objects are required to handle the interchange of data via the FMI. Secondly, interface definition files are required so that EnergyPlus and CONTAM know what data they are exchanging. Finally the CONTAM project file, the interface definition files and the ContamFMU.dll file are packaged together to create an FMU file. The Contam 3D Export tool is used to generate the required EnergyPlus objects and data exchange files, and to generate the FMU object, using the CONTAM project as its input. The data exchange files generated by the tool are the variable verification dictionary, "contam.vef" and the model description file "modelDescription.xml". The tool assumes all of the "split or pass" inputs or outputs are intended to be used for data exchange. If this is not the case the user can manually edit the interface files to remove unrequired data exchange items. The methods and regulation for variable matching are described in (Dols & Polidoro, 2015). After creating our co-simulation models, we verified that the air change rates predicted by CONTAM were correctly transferred to EnergyPlus.

4.6 Parametric simulation of scenarios method

We performed the simulations using:

- Two prototype homes (1-story, 2,100 ft^2, 2-story, 2,700 ft^2)
- Envelope leakages of 1, 3 and 5 ACH_{50}
- Balanced IAQ ventilation systems in 1 ACH_{50} homes, and simple exhaust IAQ fans in the others (3 & 5 ACH_{50})
- Four CEC climate zones (1 (Arcata), 3 (Oakland), 10 (Riverside), 16 (Blue Canyon)).

Ventilation control scenarios included baseline cases with and without IAQ fans, six temperature based controls, three occupancy based controls. Each smart control type was assessed with and without accounting for auxiliary fans. Finally, each control was assessed using two different infiltration models for the controller logic (annual effective and time-varying), as allowed by ASHRAE 62.2 – 2016 (see descriptions in Section 2 and in Appendix J). In total 1,056 cases were simulated.

In order to speed up the simulation, testing, and correction of the model scenarios outlined above, the team developed a simulation parameterization and results processing tool. This tool first generates a unique .idf file for each scenario to be simulated, runs that simulation, and then processes the results. The tool generates this idf by combining multiple snippets of EnergyPlus objects (.imf files) that individually describe the models geometry, constructions, climate specific objects, control strategies, as well as the co-simulation set-up, with parameters set to values

specific to that scenario. We used a .csv file to describe each scenario and any input parameters the control strategy needs, one scenario per line. Figure 13 shows this process flow.

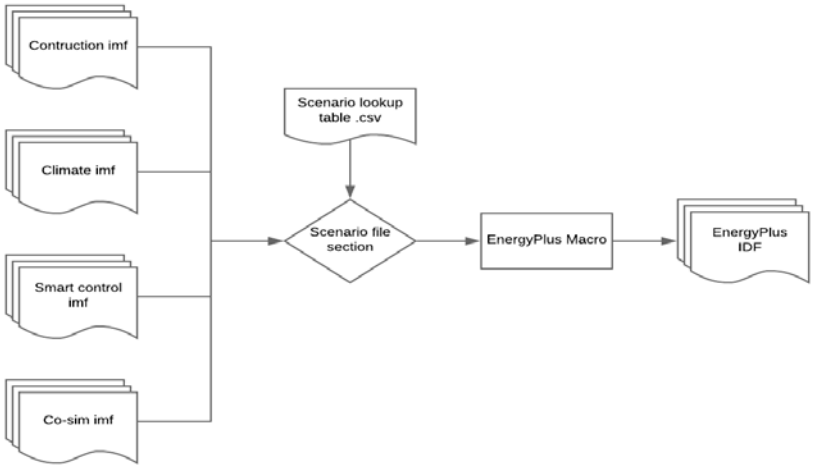
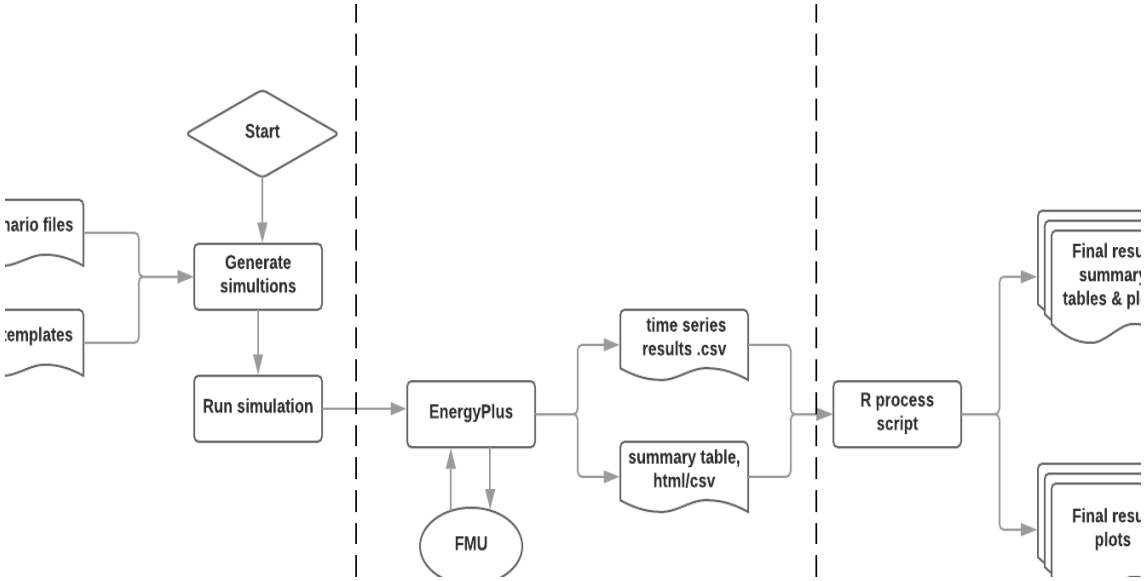


Figure 13 Generation of idf model process flow

These model variations are defined in a csv scenario definition file that describes each scenario, and gives a value for each of the scenario input parameters. Appendix M Detailed Scenario File Description, lists and describes each of the parameters representing a single row of the scenario file.

After generating a complete set of imf files, the tool then runs this batch of EnergyPlus simulations and stores the simulation results to the designated directory. Figure X gives a flow diagram describing the complete process, starting with the generation of the input idfs, then running the EnergyPlus and CONTAM co-simulation and finally processing the results and generating figures. The R-script based post processing generates both tabulated summary data and summary plots.



5 Results

The following sections describe the energy savings results generated in the simulation program. Not all cases resulted in controller relative exposure of 1, which means the IAQ is not the same in all cases.

Figure 14 illustrates the variability in energy savings and relative exposure for all the controllers. Relative exposure varied typically between 0.95 and 1.05, with some outliers in both low and high directions. Because energy savings are sensitive to exposure, we need to normalize the results by exposure if we want to identify controllers that consistently save energy, while providing the same IAQ. We will present energy savings estimates un-normalized where the relative exposures differ, and normalized by relative exposure to ensure equivalent IAQ. The non-normalized cases are what we would expect to happen if a controller were used in an individual home. The normalized results are more useful for policy decisions, for example, where we want a more apples-to-apples comparison when comparing potential energy saving strategies.

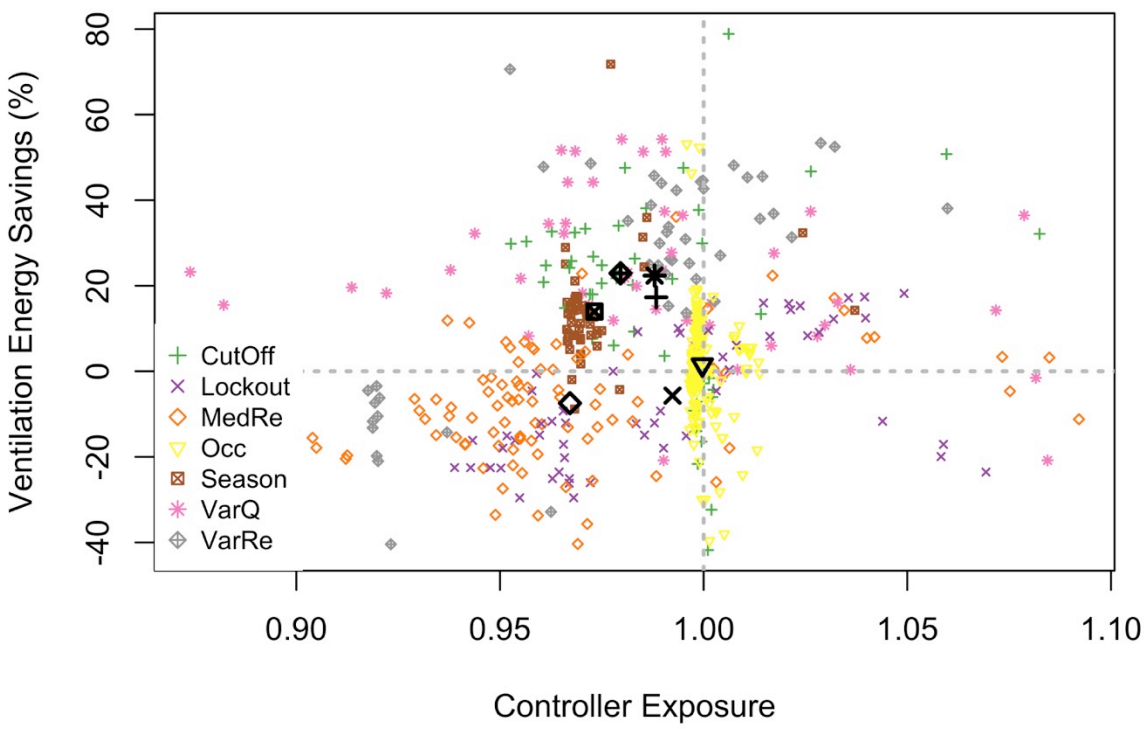


Figure 14 Controller relative exposure vs. ventilation energy savings (%).

In the un-normalized results we excluded simulations where annual controller exposure was greater than 1.0, unless otherwise noted. We first present an overview of un-normalized energy savings (Section 5.1), including weighted average results for each control type (Section 5.1.1), HVAC end-use savings (Section 5.1.2), maximum ventilation energy savings for each combination of prototype,

airtightness and climate zone (Section 5.1.3), and finally peak cooling power reductions during periods of grid stress (Section 5.1.4). Next, we summarize the results when controller relative exposure is normalized to 1.0 in all cases, ensuring perfectly matched IAQ (Section 5.2). Finally, we look at the performance of each controller individually (Section 5.3), using both un-normalized and normalized data in parallel.

5.1 Un-Normalized Energy Saving Summary

The distributions of site and TDV ventilation energy savings for all simulated cases are shown for each smart ventilation control type in Figure 15 (TDV savings in Figure 16). These values include all cases, irrespective of whether or not they complied with the ASHRAE 62.2-2016 requirement that annual relative exposure average less than 1.0. Overall, the best performing controllers are the CutOff, VarQ and VarRe cases, with median ventilation savings of 20-30%, and savings in individual cases as high as 50-80%.

Notably, many cases actually increase ventilation energy consumption, including the majority of Lockout, MedRe and Occupancy cases, which were the worst performers, overall. Some strategies are simply not effective at reducing ventilation energy use, largely because they increase ventilation rates, but do not sufficiently shift airflow to periods of smaller temperature differences. As discussed in Section 5.4, the Occupancy controller in fact does the opposite. It concentrates airflow in colder hours of the day and reduces ventilation during the mild mid-day periods. Even the best performing control types had cases where energy use increased, but these were all for cases located in Climate Zone 1 in Arcata, along California's north coast. This location has no cooling season, is very cold and humid, with next to no diurnal temperature variation. These climate features limited the efficacy of both our seasonal and daily controllers.

TDV ventilation energy savings are higher on average than site energy savings, despite the fact that control parameters were optimized using site energy values, which artificially focused the controls on reducing heating (lower ventilation rates in winter) as opposed to cooling energy. The same control types could be optimized using source energy or TDV energy directly, which would likely drive further cooling energy savings, and even higher TDV ventilation savings. As currently designed, the best control types had TDV ventilation savings commonly in the 30-80% range, with median values just below 50% savings. Select cases had TDV savings greater than 100%, meaning they operated like economizers and in fact reduced the ventilation load below what it was in the baseline case with no IAQ fan operating. These smart controlled fans in-fact used less energy than having no IAQ fan at all.

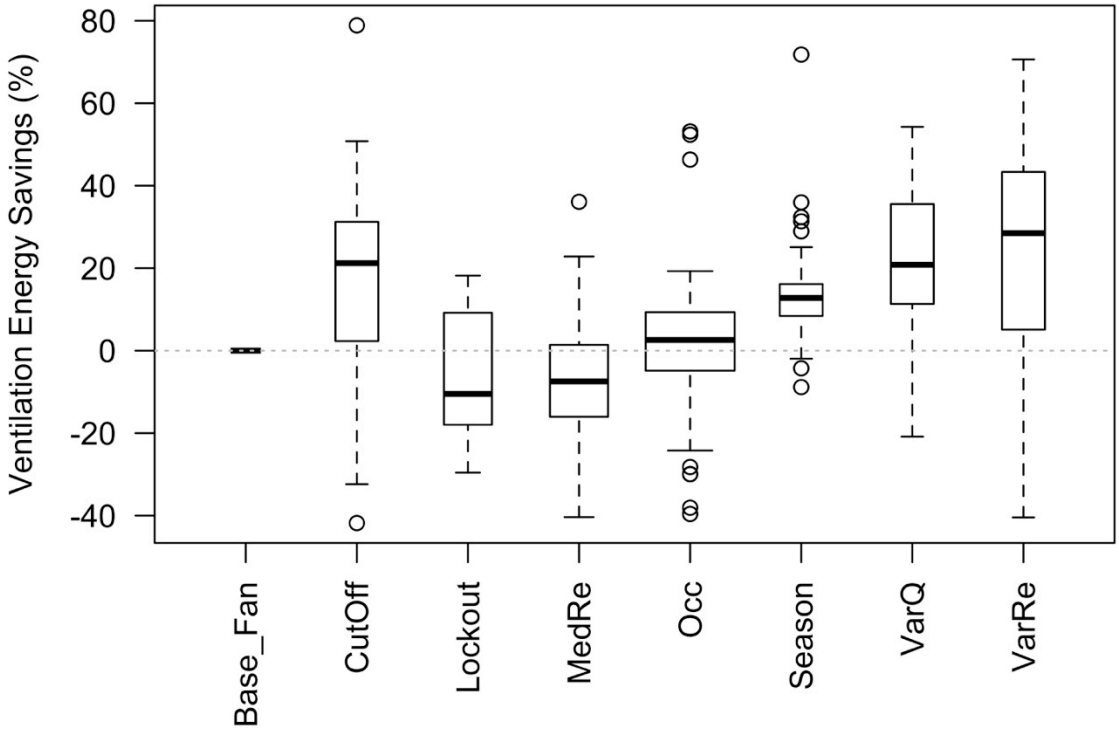


Figure 15 Ventilation energy savings (%) distribution for each smart control type, ALL cases including non-compliant.

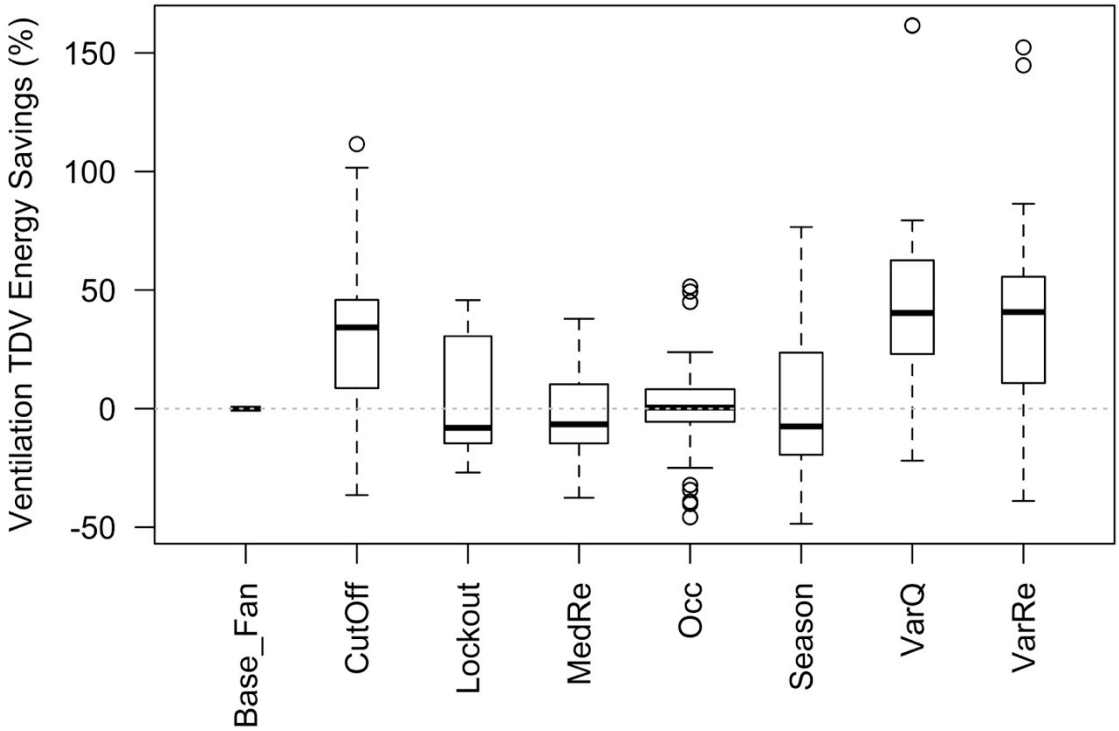


Figure 16 TDV ventilation energy savings (%) distribution for each smart control type, ALL cases including non-compliant.

5.1.1 Weighted Average Results

To generate an overall best estimate of the efficacy of the SVC strategies tested in our simulations across new homes in California, we calculated weighted average results for exposure, air exchange and ventilation site and TDV energy savings (see Appendix N for our weighted average method). These weighted average values are presented without auxiliary fan sensing in Table 6 and with auxiliary fan sensing in Table 7.

Overall, the top performing strategies for site energy savings are CutOff, VarRe and VarQ, with ventilation site energy savings ranging from 31-39%, while increasing the whole house ventilation substantially from 0.289 hr^{-1} in the baseline to 0.37 or 0.38 hr^{-1} (by roughly by one-third). While potentially unintuitive, in order to be equivalent with the exposure at a fixed airflow, the average of time-varying flows must be increased (Nazaroff, 2009). The smart controls compensate for this greater overall airflow requirement and still save energy by shifting ventilation away from extreme weather and towards mild periods. The worst performing controls increased energy use, because they failed to sufficiently shift these increased airflows to periods of mild outdoor temperature. Most of the control types achieve ASHRAE 62.2-2016 compliance in 70-90% of the cases, with the most complex, seasonal-shifting controls having the lowest compliance fractions.

In all control types, the weighted average real exposure is less than the estimated control exposure, because of inclusion of auxiliary fan airflows in the real air flow estimate. The real exposure calculation is also impacted by time varying natural infiltration that could either increase or decrease the real effective ventilation rates.

Site energy and TDV energy often show substantially different results. The VarQ controller shows strongly elevated TDV ventilation energy savings (64%), much higher than the other top-performing CutOff and VarRe controls (30 and 34%). This is because the VarQ controller saves more cooling energy than the other top performers (see Section 5.1.2) by fully turning the IAQ fan off during peak cooling hours, rather than just reducing the ventilation rate, as is done by the VarRe and CutOff controls. This gets greater credit in TDV assessments, due to higher multipliers for electricity vs. natural gas, especially during peak cooling periods. Similarly, the Seasonal and Occupancy controls both have positive ventilation site energy savings paired with increased TDV energy use, again due to the emphasis of TDV assessments on electrical cooling consumption during peak hours. Particularly for the Seasonal controller, weighted average site savings are 13%, while TDV ventilation energy use increases by 24%. Unfortunately, this is predictable based on the structure of the controller, which reduces ventilation rates in the heating season and increases ventilation during the cooling season, when strong TDV penalties exist during peak hours. The Occupancy controller turns ventilation off during the daytime hours, but then doubles ventilation airflows during the late afternoon when occupants return home, once again with predictable impacts during peak cooling hours.

While less robust than our ventilation energy savings, the EnergyPlus simulations estimate whole house HVAC savings of 9-11% for the top performing controls and slightly lower TDV whole house savings of 5-10%.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Real Exposure*	*AER (hr^{-1})*	*Site Energy*			*TDV Energy*		
					Ventilation (%)	*Total (kWh /year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh /year)*	*Total (%)*
Baseline Fan	NA	1.038	0.996	0.287	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	3.085	2.398	0.135	100.0	1182	27.3	100.0	4157	16.0
CutOff	75	0.975	0.870	0.386	31.3	370	8.5	29.7	1235	4.8
Lockout	58	0.979	0.943	0.322	-3.0	-36	-0.8	13.9	579	2.2
MedRe	84	0.962	0.892	0.344	-2.0	-23	-0.5	18.6	775	3.0
Occ	79	0.998	0.943	0.285	3.6	43	1.0	-0.4	-17	-0.1
Season	96	0.973	0.876	0.364	12.9	153	3.5	-24.4	-1015	-3.9
VarQ	69	0.972	0.878	0.371	39.4	465	10.8	63.8	2654	10.2
VarRe	77	0.982	0.872	0.377	39.2	464	10.7	33.5	1394	5.4

Table 6 Weighted average summary results for SVC without auxiliary fan sensing, including relative exposure, air exchange rates, site and TDV energy savings.

Including auxiliary fan sensing boosts ventilation site energy savings by 5 to 15% (see Table 7), due to reductions in air exchange rates. Though still compliant with ventilation standards, this increases the real contaminant exposure. VarRe weighted average TDV savings increase a lot more than the VarQ TDV savings when including auxiliary fan sensing. Yet, VarQ still outperforms the VarRe, with 69 vs. 47% weighted average TDV savings.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Real Exposure*	*AER (hr^{-1})*	*Site Energy*			*TDV Energy*		
					Ventilation (%)	*Total (kWh /year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh /year)*	*Total (%)*
Baseline Fan	NA	0.948	0.996	0.287	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	2.271	2.398	0.135	100.0	1181	27.3	100.0	4155	16.0
CutOff	94	0.936	0.911	0.371	39.9	472	10.9	35.8	1486	5.7
Lockout	53	0.983	1.005	0.307	14.3	169	3.9	27.1	1125	4.3
MedRe	94	0.952	0.972	0.311	15.7	186	4.3	32.7	1358	5.2
Occ	94	0.991	1.016	0.266	15.8	187	4.3	12.1	502	1.9

Season	98	0.961	0.949	0.338	27.9	330	7.6	-6.8	-284	-1.1
VarQ	90	0.925	0.920	0.351	47.6	562	13.0	68.7	2853	11.0
VarRe	98	0.945	0.926	0.357	49.4	584	13.5	46.9	1950	7.5

Table 7 Weighted average summary results for SVC with auxiliary fan sensing, including relative exposure, air exchange rates, site and TDV energy savings.

5.1.2 Savings by End-Use

Energy end-use savings are aggregated by control type and plotted in Figure 17 for both site and TDV energy. Site energy (right-hand panel) is strongly dominated by heating energy savings in all controls, with over 90% of total savings falling into the heating category (except for Occupancy, due to its IAQ fan savings). TDV energy end-use savings shift more towards an even divide between heating and cooling category savings. In the best performing controls (VarQ, VarRe and CutOff), cooling end-use TDV savings make up roughly 50% of total TDV savings. Time dependent valuation energy use focuses more on electrical cooling energy use during peak times, which helps to explain these higher fractions of cooling TDV energy savings. Air handler savings (and IAQ fan increases) also grew as a fraction of the total TDV energy.

The VarQ controller had the greatest TDV savings, largely because of its improved cooling performance. The VarQ control fully turned the smart IAQ fan off during particularly hot periods, which aligned almost perfectly with peak TDV hours in the summer. The CutOff and VarRe controls, in contrast, only reduced ventilation rates during these hours, rather than fully curtailing them. The Seasonal controller predictably increased cooling energy consumption, both site and TDV, because it increased ventilation rates during the cooling season and decreased them in heating, with predictable cooling energy penalties. The emphasis of TDV energy performance on electricity consumption during peak cooling hours leads to this net-negative effect.

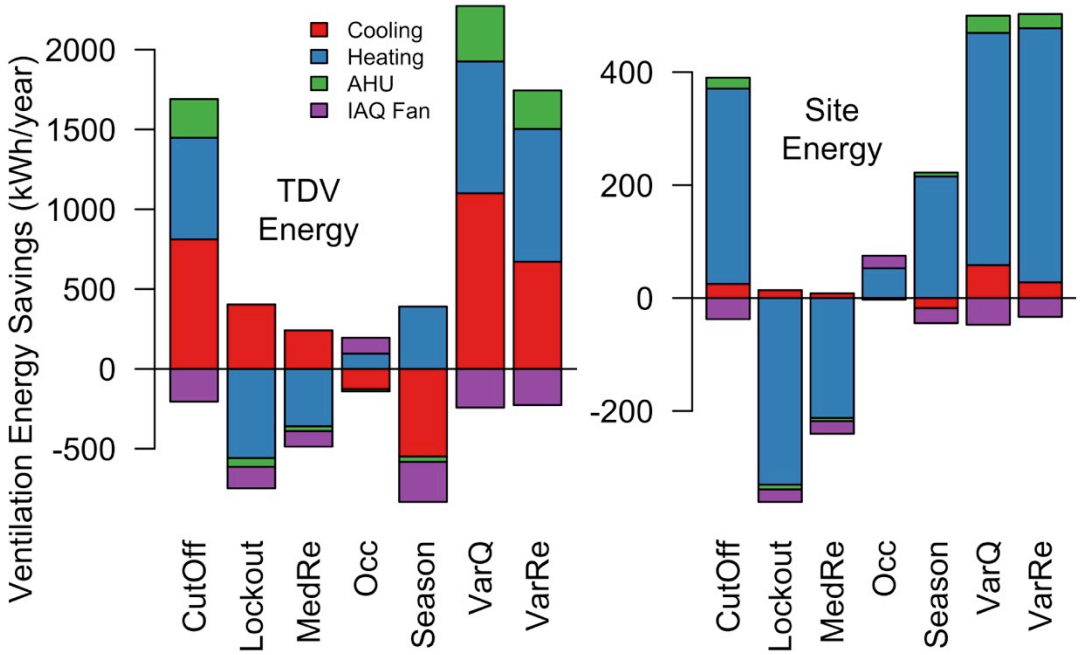


Figure 17 Median ventilation energy savings by end-use category, site and TDV energy. Aggregated by control type.

5.1.3 Maximum Savings for Each Case

In each of the 24 cases (i.e., combinations of climate, house prototype and airtightness), we identified the smart control strategy with the maximum ventilation energy savings. Ventilation energy savings for these best-performing controls are plotted below for site energy % savings (Figure 18), site energy kWh savings (Figure 19), TDV energy % savings (Figure 20) and TDV energy kWh savings (Figure 21). Along with ventilation energy savings, each plot also includes the change in real relative exposure, with negative values indicating improvement in IAQ relative to the baseline constant fan case. As illustrated below, ventilation site energy can be reduced by 15-50%, saving 200-1,500 kWh/year, and ventilation TDV energy can be reduced even more, varying roughly between 10 and 75%, saving 300-4,000 kWh/year of TDV energy. This is achieved while complying with the ASHRAE ventilation standard requirement that annual occupied relative exposure be below 1.0. In fact, most of the best performing cases reduced real exposure and improved IAQ relative to the baseline constant fan cases.

Across these four energy savings metrics, we see that the VarRe and VarQ controls consistently save the most energy, with select cases having greatest savings with Season, CutOff or Occupancy. Specifically, the temperature controls were generally ineffective in CZ1 (Arcata), so in those cases, occupancy-based smart controls often had the greatest savings, albeit at low levels and sometimes with increased energy use.

Percent ventilation savings and absolute kWh savings have related but distinct patterns. For example, percent site savings appear greatest in CZ10, varying between roughly 35-50%. Yet, absolute kWh site savings are similar in CZ3 and CZ10, and are in fact substantially larger in CZ16. This highlights an important distinction, which is that the baseline IAQ fan ventilation energy use varies across climates, and savings are referenced against that baseline usage. Baseline ventilation energy use is sensitive to climate region (energy use is greatest in cold locations) and to baseline IAQ fan airflows, which are affected by envelope leakage and house prototype.

So, similar absolute savings, or even greater absolute savings can appear as less successful in terms of percent savings. This is evident for differing levels of envelope leakage, as well, because the baseline IAQ fan flows are smaller in leakier homes. For example, percent site savings appear consistent across the 1, 3 and 5 ACH_{50} 1-story homes in CZ10 (if anything savings increase with leakage), yet when assessing absolute kWh savings, we see that the leakier cases in fact save less energy than their tight counterparts. The absolute energy savings (both site and TDV) show this reasonably consistently: that the most airtight homes save the most absolute energy, but often have marginally lower percent savings. House prototypes have mixed effects. In some climate zones, the 1-story cases appear to have the greatest savings, while in other climates the 2-story are the best performing. This inconsistency exists for both percent and absolute energy savings.

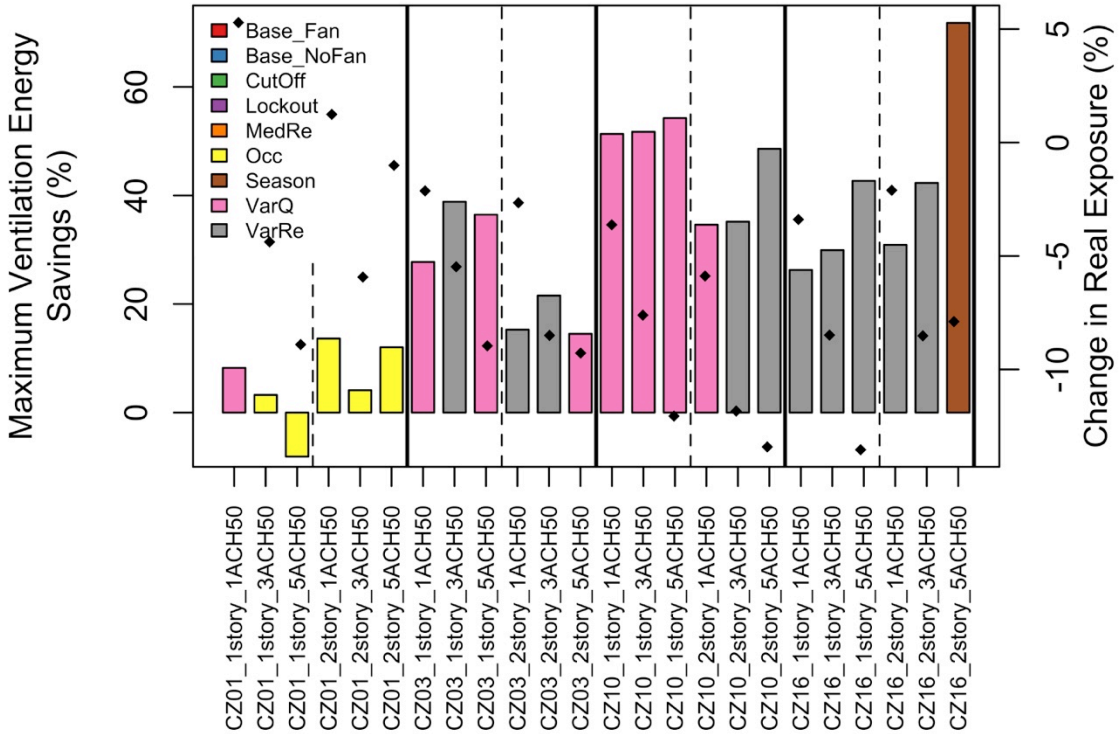


Figure 18 Maximum ventilation energy savings (%) for each compliant case. Colored by control type. Diamond symbols show the change in real relative exposure for the maximum savings case. Negative changes in real exposure represent improved IAQ.

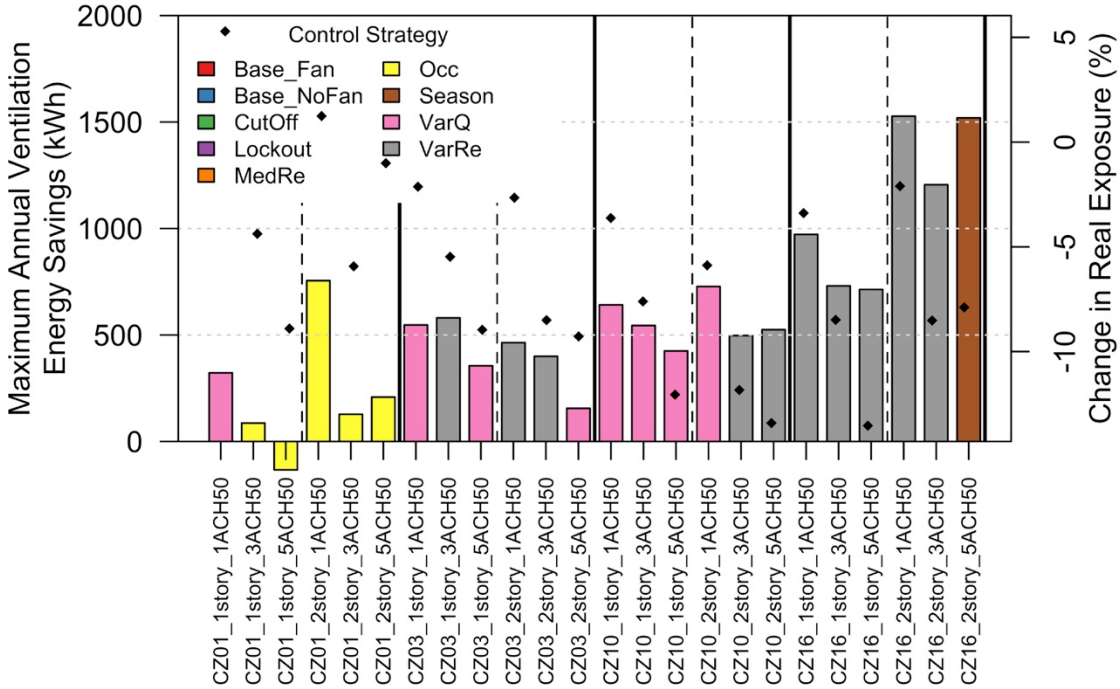


Figure 19 Maximum ventilation energy savings (kWh) for each compliant case. Colored by control type. Diamond symbols show the change in real relative exposure for the maximum savings case.

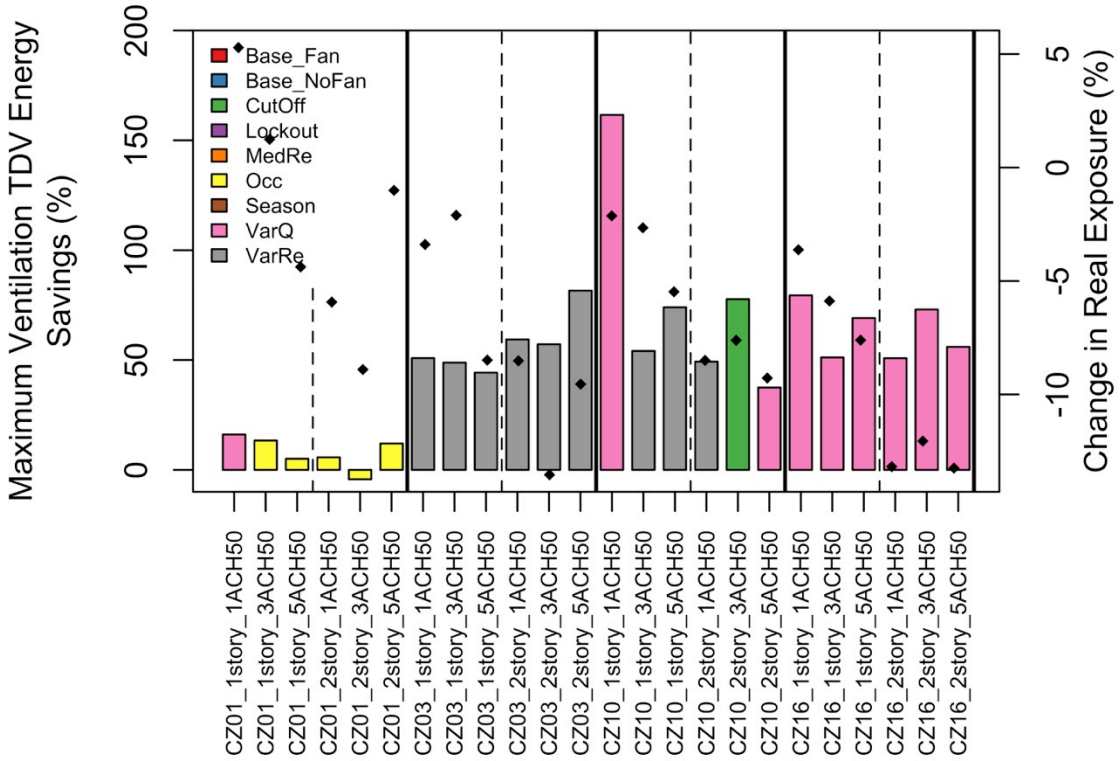


Figure 20 Maximum TDV ventilation energy savings (%) for each compliant case. Colored by control type. Diamond symbols show reduction in real relative exposure for the maximum savings case.

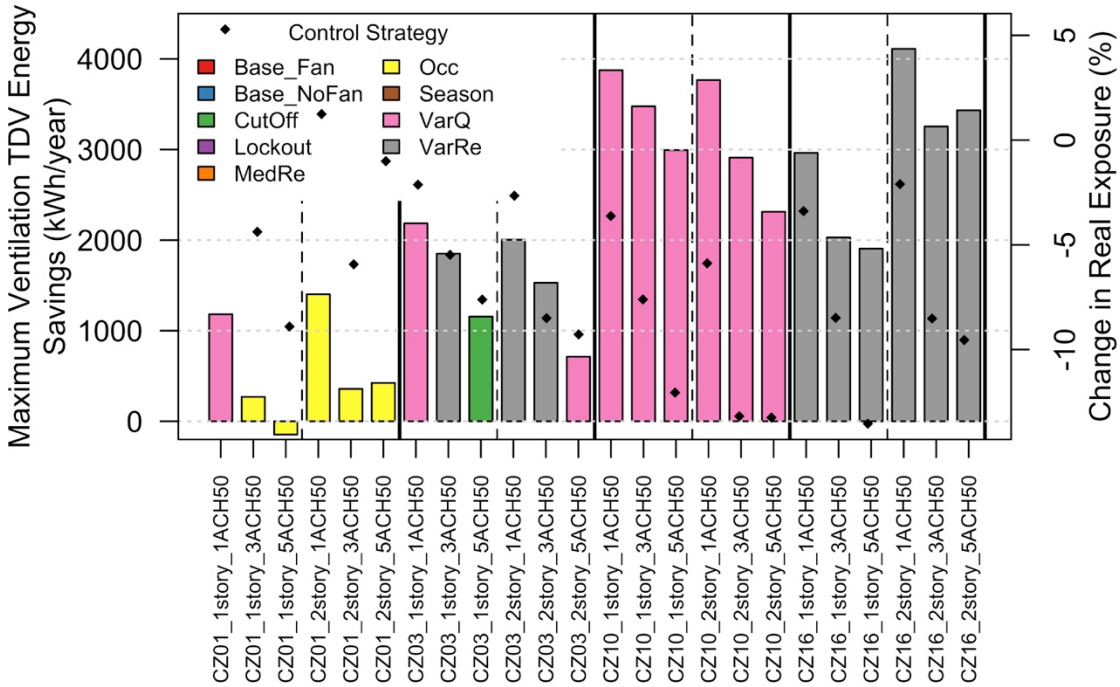


Figure 21 Maximum TDV ventilation energy savings (kWh) for each compliant case. Colored by control type. Diamond symbols show reduction in real relative exposure for the maximum savings case.

5.1.4 Peak Demand Savings

None of these controllers were specifically optimized around shedding peak load. Nevertheless, we assessed peak demand by looking at average watt draw and total site and TDV energy consumption during the peak 2-6pm period on the hottest 10-days of the year, according to the weather files for each climate zone. We show the demand reduction in watts and in percent of total site HVAC energy use aggregated by control type in Figure 22 and Figure 23, respectively. Using only cases from one of the most effective peak saving controls (VarRe), we then show peak demand reduction (watts) by climate zone in Figure 24.

Changes in peak demand varied from roughly a 100-watt increase to savings of 400 watts during peak periods. For the most successful control types (VarRe, VarQ, Lockout and Cutoff), this translated into 0-20% of total HVAC site energy consumption during the peak periods. As we show in Figure 24, for these well performing controls, the energy use increases occur only in CZ1 in Arcata, where slightly more cooling load is introduced. This happens because the controllers think that there is no cooling season in Arcata, so they over-ventilate substantially during the warmest periods, increasing the cooling load very marginally (i.e., total cooling consumption for all CZ cases was 3 or 0 kWh/year).

We also see that for the VarQ controller (and others) savings are greatest in CZ10, which has the highest cooling demand of any location we assessed. Notably, the VarRe controller had quite low (<100 watts) savings in CZ10, because the optimized control parameters did not sufficiently reduce ventilation rates during hot weather,

rather they emphasized ventilation rate reductions in the heating season. This issue could be avoided by using TDV energy directly in the optimization schemes, or by not independently optimizing heating and cooling season peak RE values, which should lead to larger reductions in ventilation during hot periods (see Section 3.1.5 and Appendix F).

It is worth noting that HVAC sizing has substantial impacts on the potential for peak load reductions in homes. In fact, early rounds of our simulations revealed that the simulated cooling systems in CZ10 were slightly under-sized (they were increased to appropriate levels in all subsequent simulations), such that the cooling runtime was 100% during the peak 2-6pm periods of the hottest days of the year, in both baseline and control cases. When this happens, no savings are registered, though the smart control case will have slightly lower loads and cooler indoor temperatures. This demonstrated an important point, which is that "right" sized HVAC systems, which are designed to more or less run continuously during design conditions, will have essentially no ability to reduce peak demand on the grid. This is also the case for any systems that run continuously during peak periods, whether "right" sized or not.

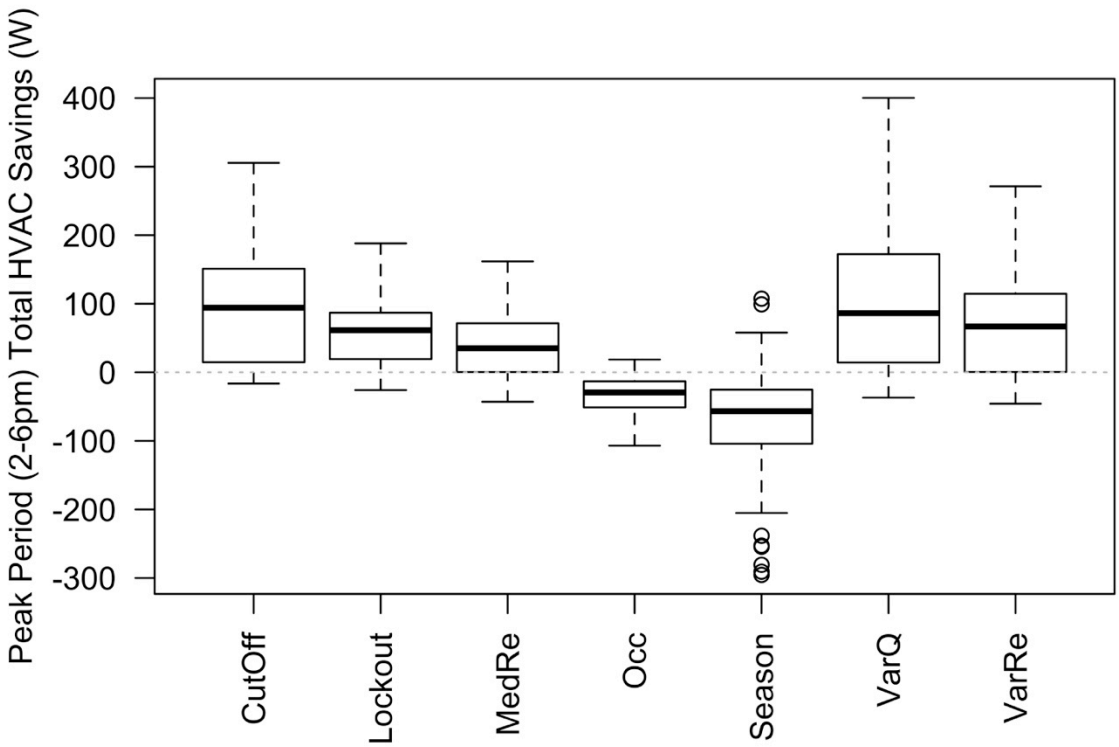


Figure 22 Peak demand (Watts) reduction on the 10 hottest days of the year, 2-6pm, by control type.

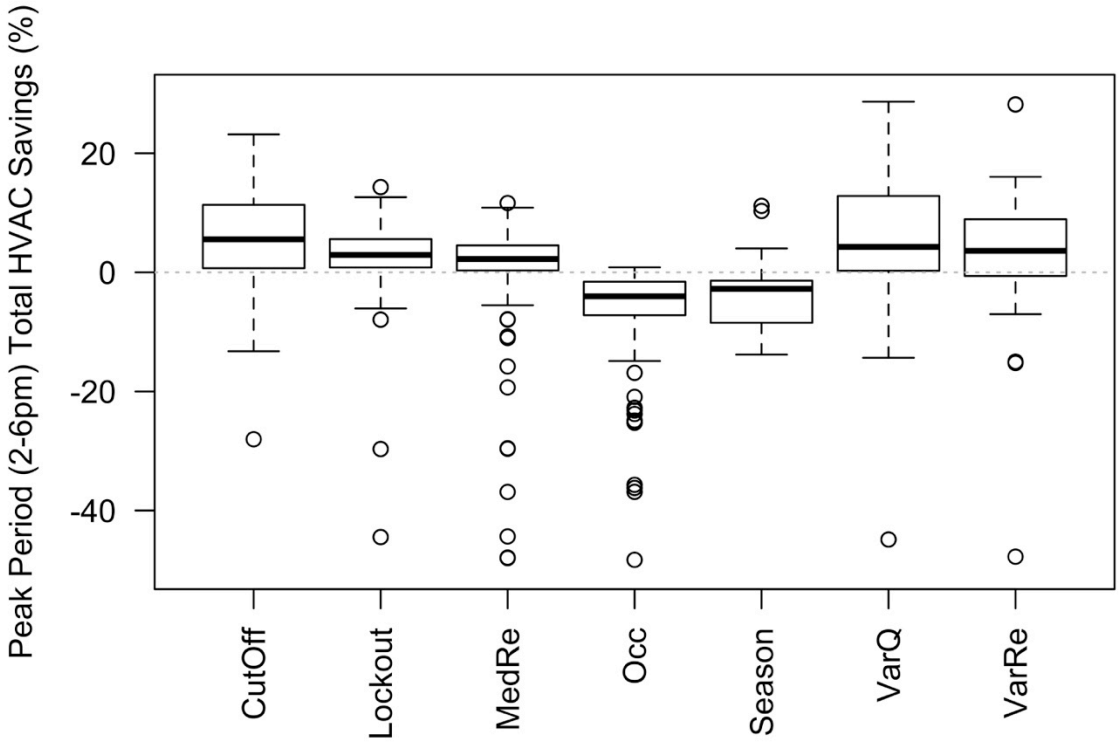


Figure 23 Total HVAC site energy savings on the 10 hottest days of the year, 2-6pm, by control type.

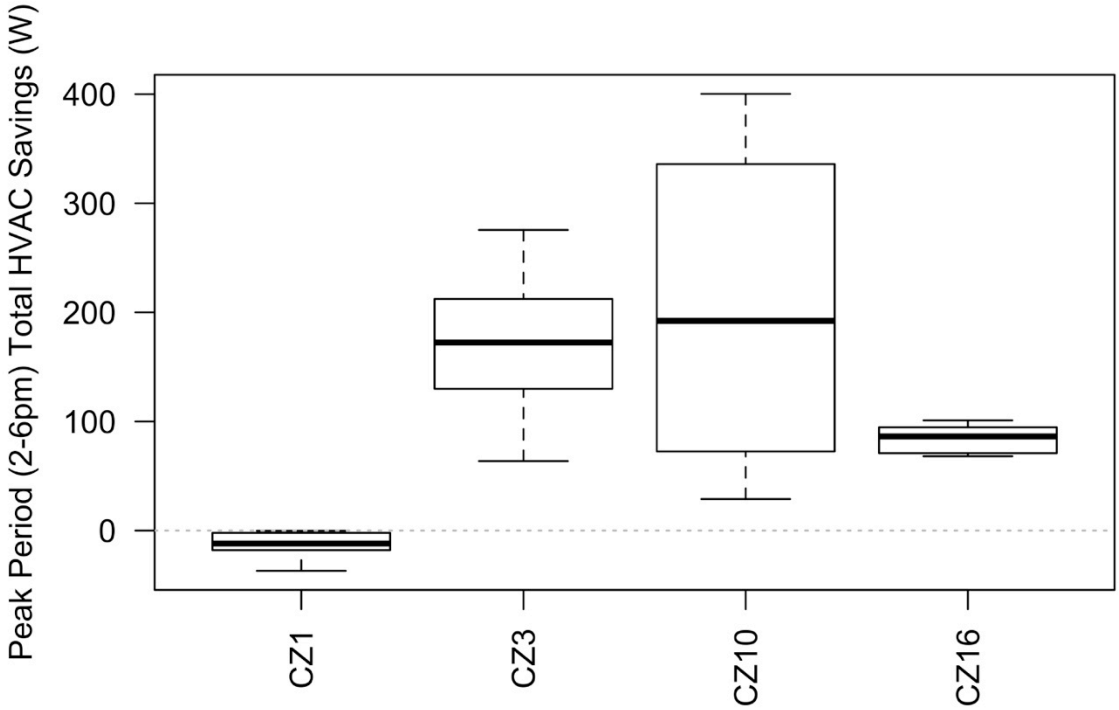


Figure 24 Peak demand (Watts) reduction for the VarQ controller on the 10 hottest days of the year, 2-6pm, by climate zone.

5.2 Normalized Energy Savings Summary

In the raw simulation outputs presented in the prior sections, the relative exposure is not always equal to one, either in the baseline continuous fan or smart control cases. So, the energy savings are estimated for cases where the predicted indoor air quality is not the same. To provide energy savings estimates for cases with identical IAQ, we also normalized the site and TDV energy results by the annual mean controller exposure for each case. These normalized results represent the performance of perfectly designed/operated smart ventilation controls, compared with perfectly sized baseline continuous IAQ fans. The normalization method is explained in Appendix O.

We compare the normalized savings values with the previously presented raw savings results on a case-by-case basis below. Scatterplots of the percent ventilation energy savings are shown for site energy in Figure 25 and for TDV energy in Figure 26, with all baseline cases removed from analysis. Each scatterplot includes the unity line with a slope of 1 (red) and a linear regression line (blue). For both site and TDV energy, we see that normalization tended to increase predicted ventilation energy savings in most cases (most values are above the red unity line and so is the blue regression line). Select cases had reduced savings when normalized. These are smart control cases that had relative exposures greater than one, so normalization actually increased their predicted energy consumption and reduced their savings relative to the baseline continuous fan cases. The lowest performing cases in terms of raw savings had the greatest benefits from normalization (savings increased 0 to 40% for these cases), while the increase in normalized savings lessened as the raw savings grew larger. At the higher end, when raw savings were in the 40-50% range, normalization commonly increased the savings by only 5-10% (e.g., from 40 to 45% or 40 to 50%).

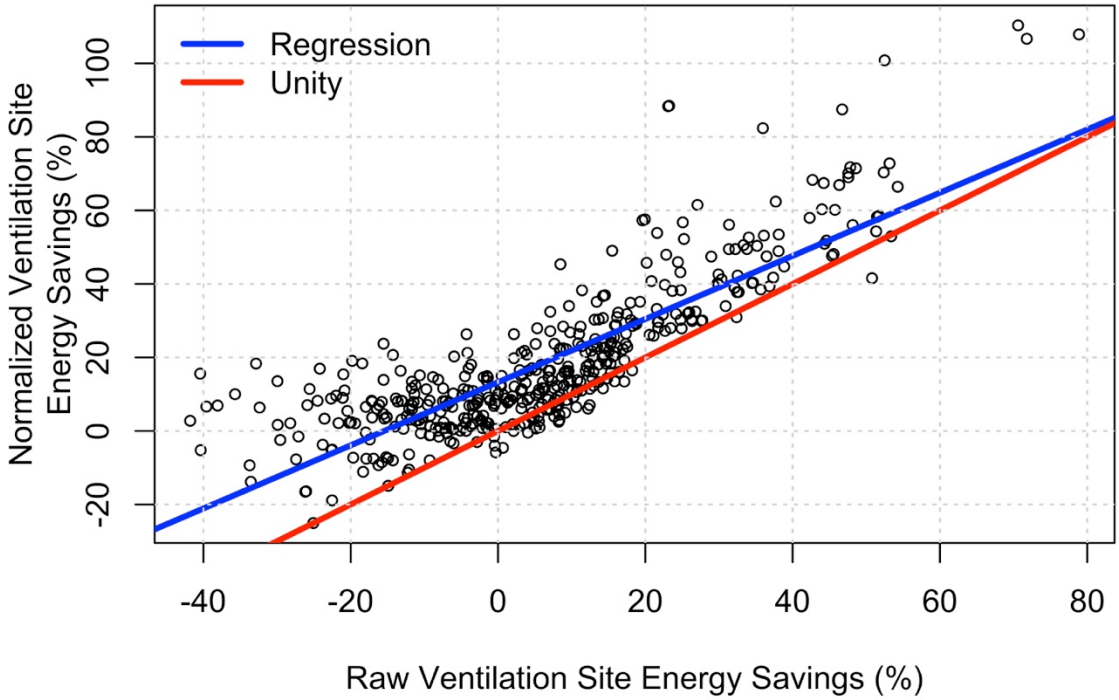


Figure 25 Scatterplot comparing raw vs. normalized site HVAC energy savings. Baseline cases removed.

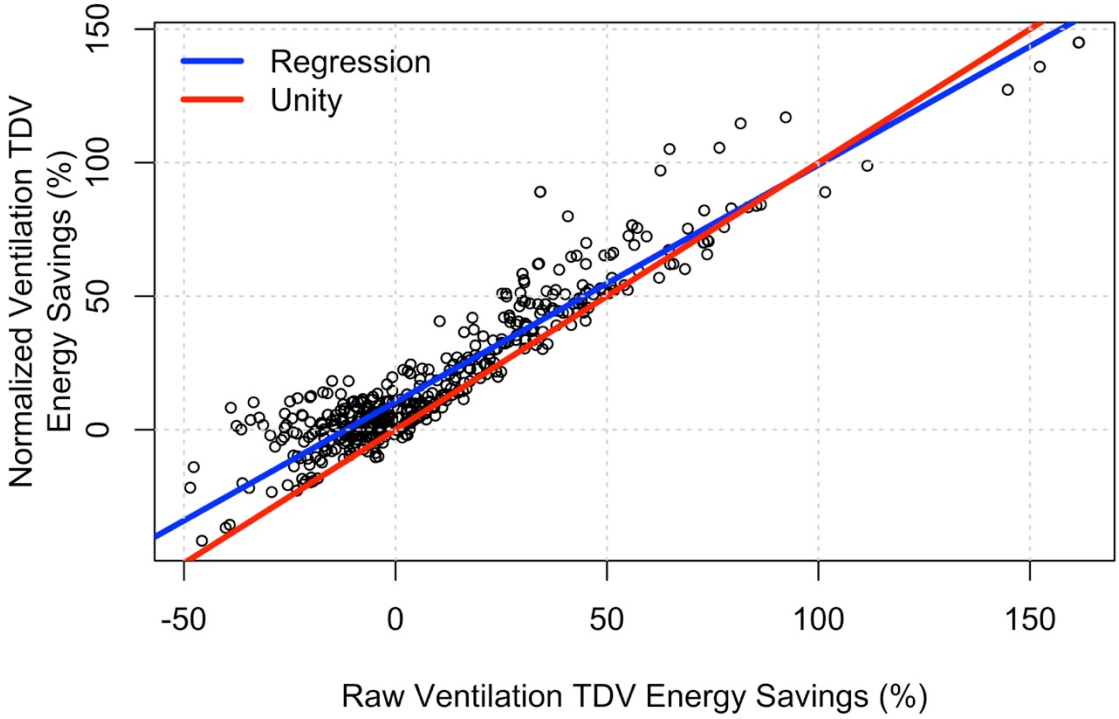


Figure 26 Scatterplot comparing raw vs. normalized TDV HVAC energy savings. Baseline cases removed.

5.2.1 Weighted Average Results

The weighted average normalized performance for each control type is summarized in Table 8 with no auxiliary fan accounting. Compliance fractions are 100% and all controller exposure values were 1.0. The real exposure and air exchange rates were not normalized and are not reported.

The weighted average site energy performance for the VarQ and VarRe controllers are very similar, with average ventilation energy savings of 54% and 55% (site savings of 634 and 651 kWh/year), respectively. These represent total HVAC site savings of roughly 15%. For comparison, these same two controllers both had 39% ventilation site savings for un-normalized, compliant cases (see Table 6 in Section 5.1.1). The Cutoff SVC was the next best performing controller (mean savings of 48%), while all others lagged substantially behind these top performers, with savings between 10 and 30% of site ventilation energy.

TDV ventilation savings were clearly the greatest for the VarQ controller, with weighted average savings of 72%, compared with 50 and 46% in the VarRe and CutOff controllers. TDV energy savings averaged 2,953 kWh/year in the VarQ cases, representing 11% of total HVAC TDV consumption.

The trends in these results are similar to those based on the raw results (see Section 5.1.1), but the savings are roughly 10% higher on average when normalized. The other notable difference is that no control types increased ventilation energy use on a weighted average basis, whereas the raw results had some controllers with negative savings. The Seasonal control remains an exception to this for TDV energy, which still marginally increased consumption.

The three best controls (VarQ, VarRe and CutOff) all shifted ventilation airflows seasonally, with increased flows during summer and reduced flows during winter. In addition, within each season, the best controls also modulated airflows in response to mild or severe conditions. Without this modulation within each season, savings were reduced, as reflected in the weighted average savings for the Season controller (29%). These results suggest that modulation of flows within the season gains another 20-25% ventilation energy savings on top of season-based control. Conversely, the controls that shifted ventilation only within a day (Lockout) or within a month (MedRe) suffered from low savings estimates of 11 and 15% ventilation energy. Like all dynamic smart ventilation controls, annual airflows were increased in these low-performing controls, but they failed to sufficiently shift these larger flows to milder weather periods, so savings were limited.

Control Type	*Compliance Fraction (%)*	*Controller Exposure*	*Site Energy*			*TDV Energy*		
			Ventilation (%)	*Total (kWh/year)*	*Total (%)*	*Ventilation (%)*	*Total (kWh/year)*	*Total (%)*

Baseline Fan	NA	1	0.0	0	0.0	0.0	0	0.0
Baseline No Fan	NA	1	100.0	1178	27.3	100.0	4097	15.9
CutOff	1	1	47.7	561	13.0	46.3	1897	7.3
Lockout	1	1	11.3	133	3.1	33.0	1352	5.2
MedRe	1	1	14.9	176	4.1	26.4	1080	4.2
Occ	1	1	13.0	153	3.5	6.8	277	1.1
Season	1	1	28.9	340	7.9	-2.2	-91	-0.4
VarQ	1	1	53.8	634	14.7	72.1	2953	11.4
VarRe	1	1	55.3	651	15.1	49.7	2036	7.9

Table 8 Weighted average savings estimates for normalized energy consumption. NA values were not subject to the normalization, so are excluded.

5.2.2 Maximum Savings for Each Case

For each simulated home (i.e., combination of climate zone, prototype and airtightness), we selected the control type with the highest energy savings. These are shown for site energy savings (relative in Figure 27 and absolute in Figure 28) and TDV energy savings (relative in Figure 29 and absolute in Figure 30). As expected from the weighted average results in Table 8, the VarQ (pink) and VarRe (grey) controllers are most commonly the best performing for any given home, with some individual cases maximizing savings with the MedRe, CutOff or Occupancy controllers. With the exception of CZ1, most cases were able to achieve site ventilation energy savings between 20 and 70% (500 to 2,000 kWh/year). TDV ventilation energy savings ranged between 50 and 80% (1,000 to 4,000 kWh/year TDV).

When normalized, the percent site energy savings consistently increase with envelope leakage. This is true for all homes and climates. This effect was greatest in CZ16 and least in CZ1 and CZ10. This is because of the interactions between natural infiltration (that vary with airtightness) and mechanical ventilation. The absolute site energy savings do not show the same trend. Instead the site kWh savings vary slightly and unpredictably across envelope leakage levels for any given home, except in CZ16 where the trend still favors greater kWh savings in leakier homes. Notably, while the percent ventilation energy savings in CZ1 were much lower than in other climate regions, the absolute savings are similar to those in CZ3, they just represent smaller fractions of the total ventilation energy consumption because the thermal loads are so much greater in CZ1.

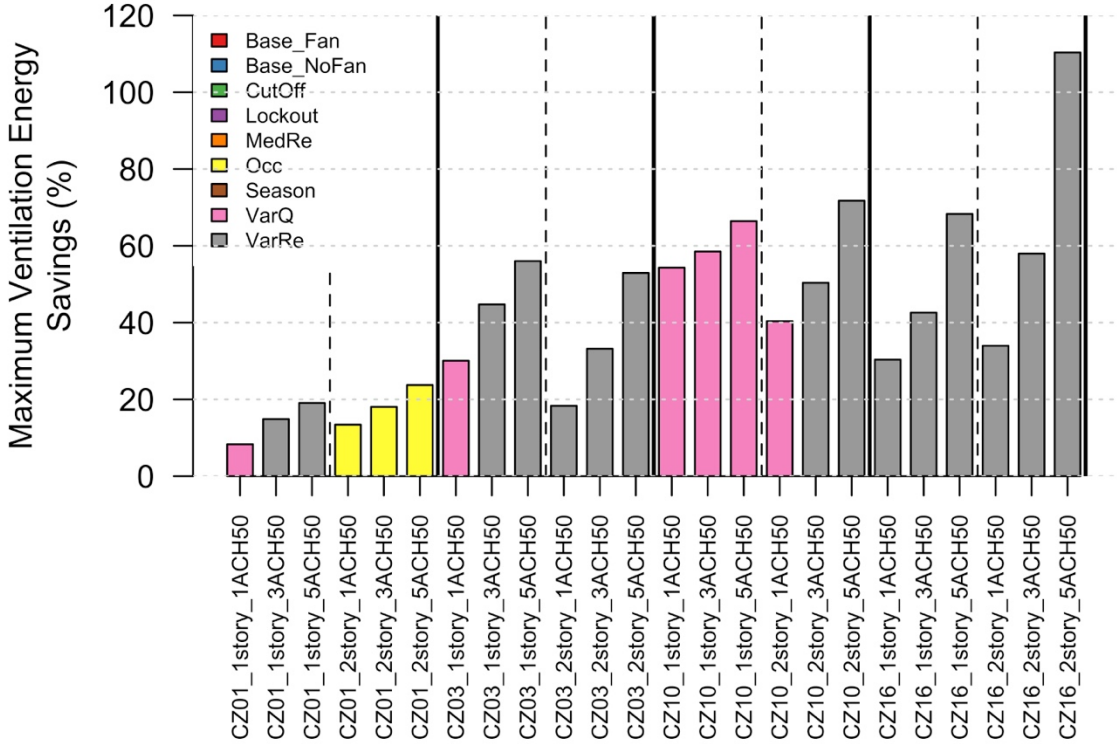


Figure 27 Normalized site energy relative savings. Maximum for each case.

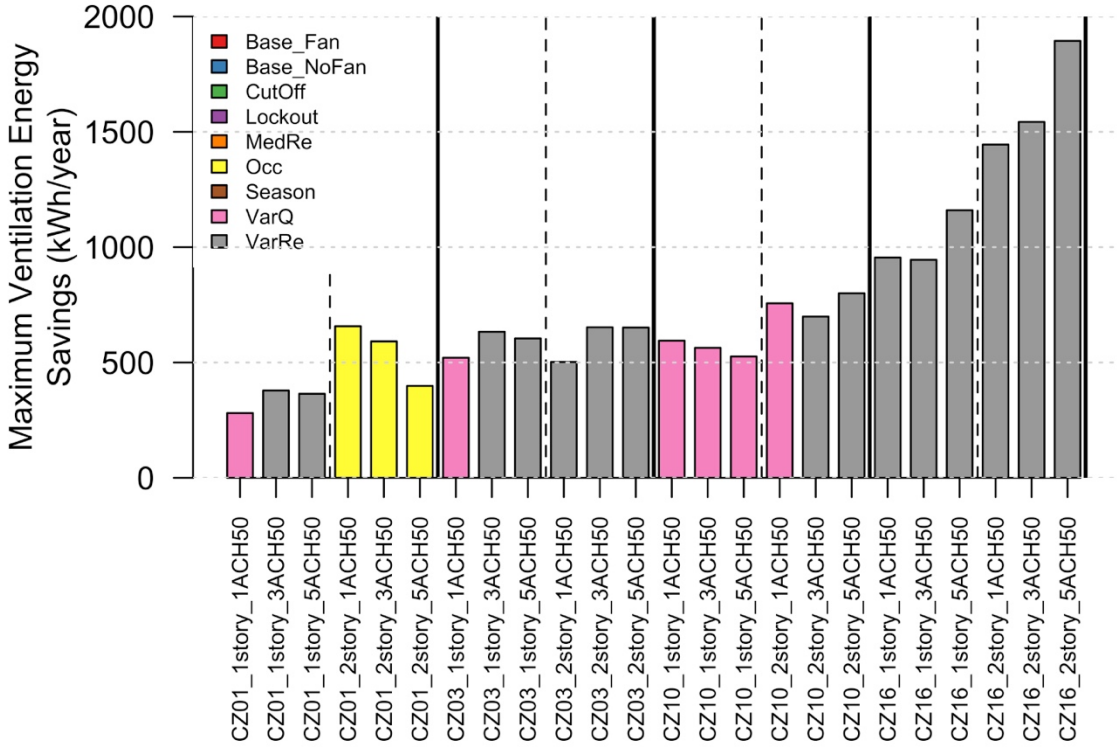


Figure 28 Normalized site energy absolute kWh savings. Maximum for each case.

Percent TDV ventilation energy savings are fairly consistent across CZ3, 10 and 16, while TDV percent savings are much lower in CZ 1 (<25%). Unlike the site energy assessment, the TDV percent savings do not show consistent increases with increasing envelope leakage. This trend is evident in some cases (i.e., CZ16), but is otherwise erratic. This could be due to the reduced dependency of TDV energy use on envelope leakage, which tends to have stronger impacts on heating energy, due to larger indoor-outdoor temperature differences. Yet, in most locations, absolute TDV kWh energy savings were still reduced as envelope leakage increases. Again, prototype impacts are mixed and lack clear trends. Notably, absolute TDV energy savings are nearly the same in CZ10 and in CZ16, which contrasts sharply with the site energy results, where CZ16 strongly dominated. As noted elsewhere, TDV energy strongly weights electricity consumption, particularly during peak cooling periods, and the VarQ controller's ability to reduce peak cooling demand ensured its absolute TDV energy savings were similar to those in the much colder CZ16 cases.

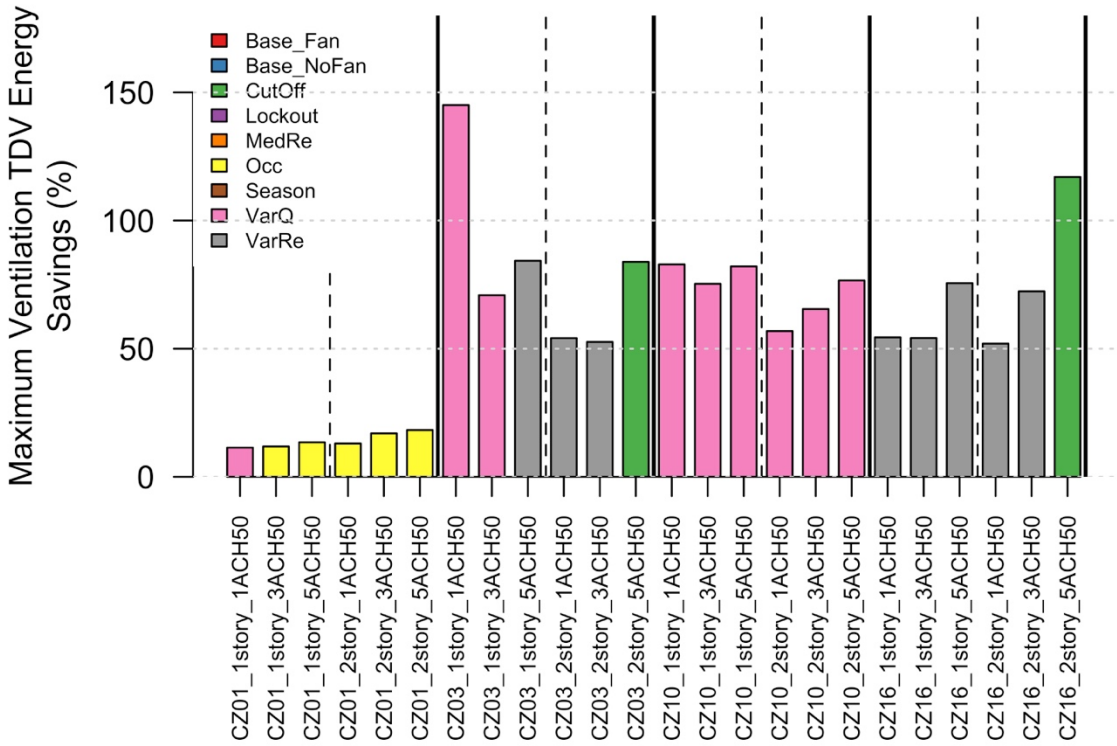


Figure 29 Normalized TDV energy relative savings. Maximum for each case.

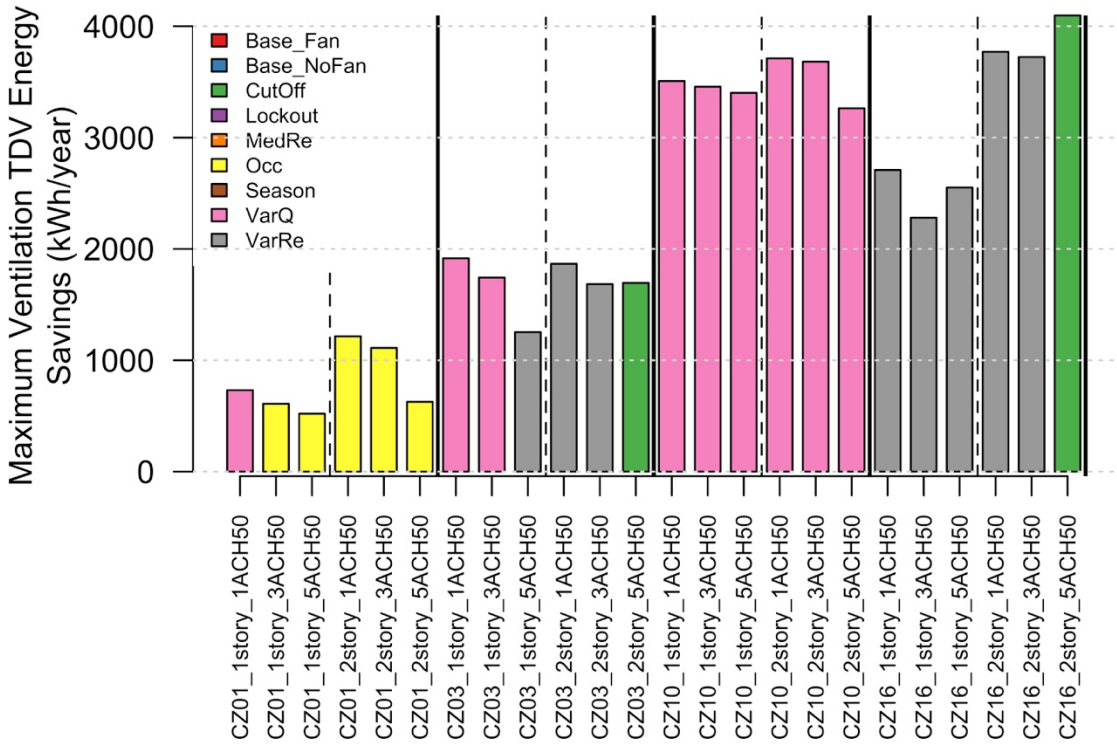


Figure 30 Normalized TDV energy absolute kWh savings. Maximum for each case.

5.3 Temperature Controls

5.3.1 Lock-Out Timer Control (Lockout)

For each case (combination of prototype, envelope leakage and climate) we show Lockout controller percent ventilation energy savings for site energy (Figure 31) and TDV (Figure 32) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 33) and TDV (Figure 34).

The results were almost unanimously negative for raw site energy savings, with 0-30% increased ventilation energy consumption in all cases, except CZ10 (Riverside) where marginal savings were estimated of less than 15% of ventilation energy. Notably, mean controller exposure in the CZ10 cases tended to be marginally greater than 1.0, which could contribute to the observed savings. All other cases had mean exposure between 0.95 and 1.0. In these cases, the additional total airflow required to maintain exposure below one overwhelmed the thermal energy benefit of the lockout period because this increases airflow over all other hours, including the hours immediately before and after the lockout period, where in these California climates the temperature differences can still be substantial. Future work may investigate optimizing the length of the off period for the lockout strategy. There are no consistent trends with envelope leakage, and the infiltration accounting method (Qing vs. AIM-2) has very little impact on savings, positive or negative. When

assessing raw TDV savings, the performance improves substantially in CZ10 (Riverside) in the most airtight homes, with 25-50% ventilation TDV energy savings. Most other cases continue to increase ventilation TDV energy use.

The normalized results are noticeably different, but the performance of the Lockout control remains marginal. Performance in CZ10 is actually worsened for the airtight cases, while the leakiest homes increase savings slightly. Also, select 3 and 5 ACH_{50} cases in CZ1, 3 and 16 shift from increased consumption to very small savings. When normalized, we clearly see that the leakiest homes have the greatest percent ventilation savings, and while very similar, the AIM-2 infiltration accounting slightly outperforms the Qing method.

These raw and normalized results suggest that a controller that shifts ventilation airflow between hours of the day will not be effective on its own, unless the diurnal temperature swings are quite large (as they are CZ10). When diurnal swings are large, the TDV energy benefit from cooling savings can be substantial. This indicates that this could be a simple and effective peak demand saving strategy. This timer-based control type has been shown to be part of an effective smart ventilation controller that combined other features, including occupancy detection and auxiliary fan sensing (Turner & Walker, 2012; Iain S. Walker et al., 2012). But in isolation, this strategy is not effective in most new California homes.

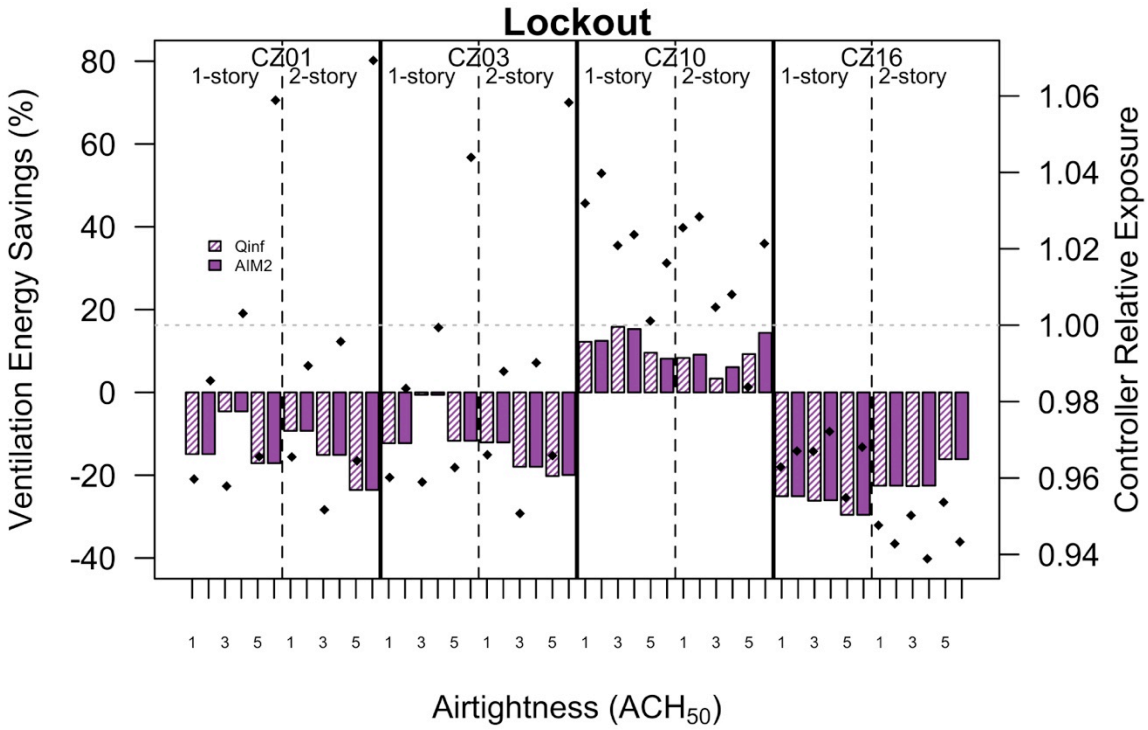


Figure 31 Lockout TSVC ventilation energy savings and controller relative exposure.

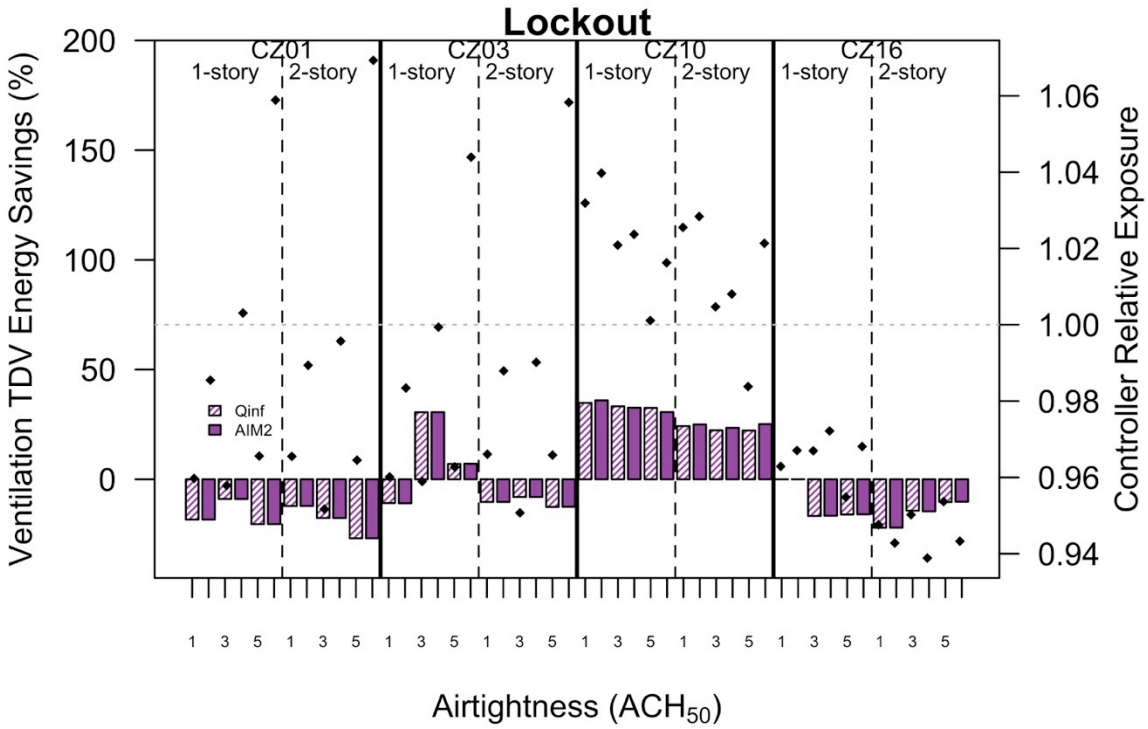


Figure 32 Lockout TSVC ventilation TDV energy savings and controller relative exposure.

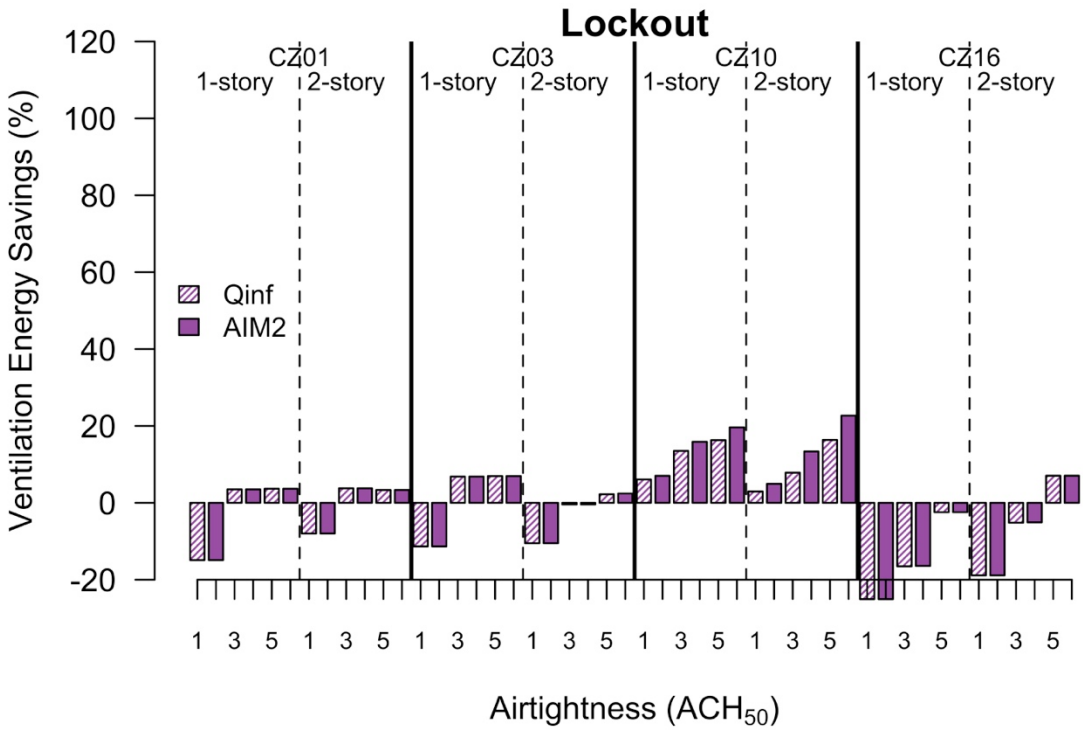


Figure 33 Lockout TSVC normalized ventilation energy savings.

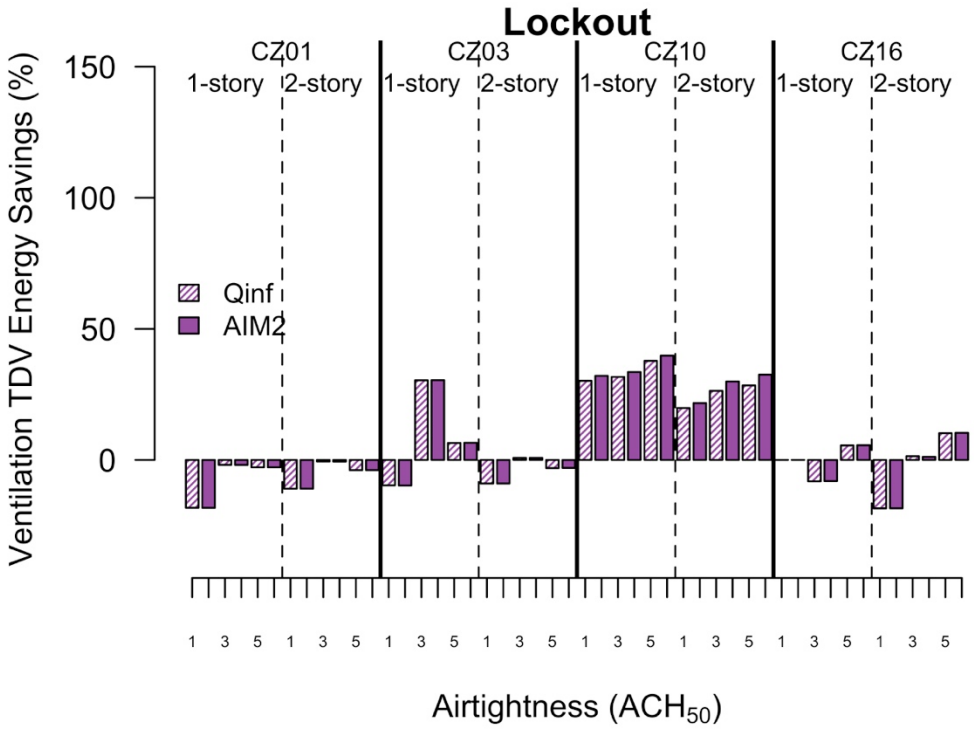


Figure 34 Lockout TSVC normalized ventilation TDV energy savings.

We also assessed the effect of varying the number of lockout hours between 4, 6 and 8 hours with the IAQ fan turned off. Longer lockout periods required larger IAQ fans to maintain exposure below one on daily and annual bases. For CZ10 (the only location with savings), we show the impact of varying lockout hours in Figure 35 for 1-story medium prototypes at 3 and 5 ACH_{50}. The savings clearly increase as the lockout period gets longer, with maximum savings in the 8-hour lockout controls. In locations with large diurnal temperature swings, an 8-hour lockout period appears best, though savings are still marginal, at 10% of ventilation energy.

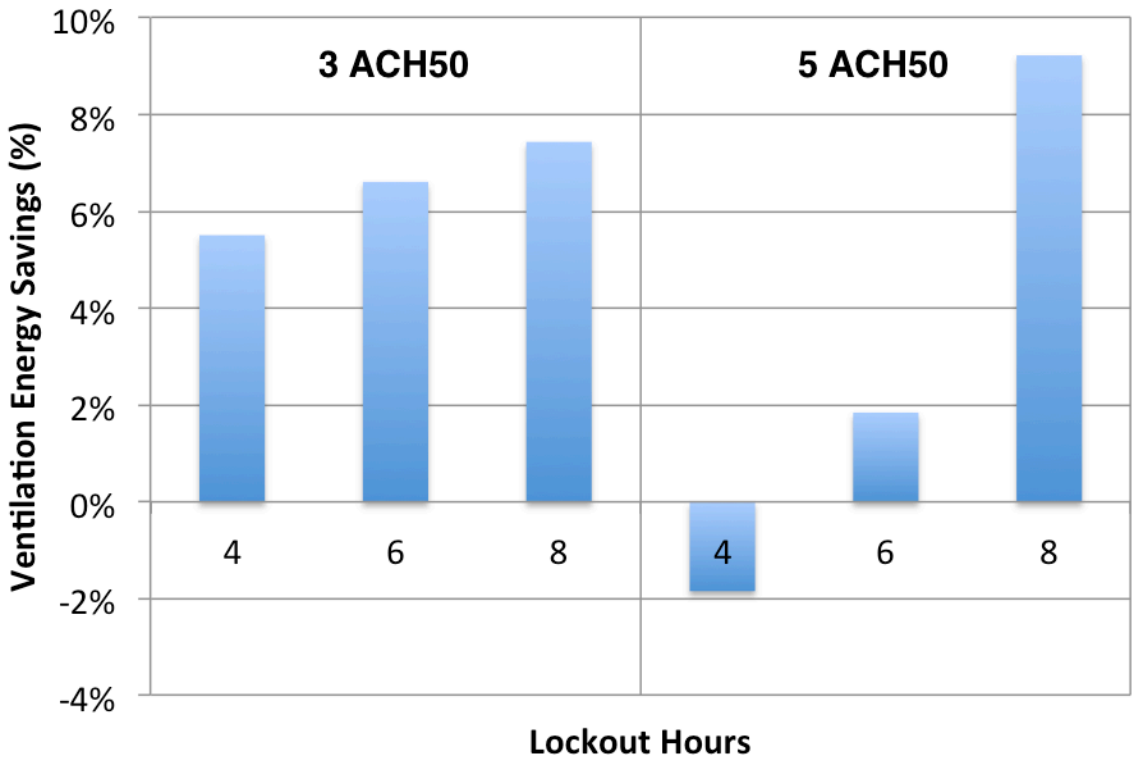


Figure 35 Effect of lockout period on Lockout TSVC performance in CZ10, 1-story medium prototypes with 3 and 5 ACH_{50} airtightness.

5.3.2 Running Median (MedRe)

For each case (combination of prototype, envelope leakage and climate) we show the Running Median controller percent ventilation energy savings for site energy (Figure 36) and TDV (Figure 37) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 38) and TDV (Figure 39).

Overall, the raw data results show that the 30-day running median controller had poor performance in most locations and prototypes, with increased energy consumption between 0 and 25% of ventilation energy. Once again, savings are evident in CZ10, as well as in some of the 2-story 5 ACH_{50} cases in other climate zones, most notably CZ16, where this controller saved almost 40% of ventilation energy in this prototype. No trends are evident by house prototype, envelope leakage, or infiltration accounting method. The raw TDV energy performance was similarly poor across all factors, with select cases in CZ10 having 20-25% savings.

When normalized by relative exposure, the increased consumption cases all turn into ventilation savings, though almost universally below 20% of ventilation site energy. Percent savings are higher with leakier envelopes and no differences are observable between house prototypes. The infiltration accounting method is varied, with marginally better performance for AIM-2 with some notable exceptions, such as the 2-story 5 ACH_{50} home in CZ16.

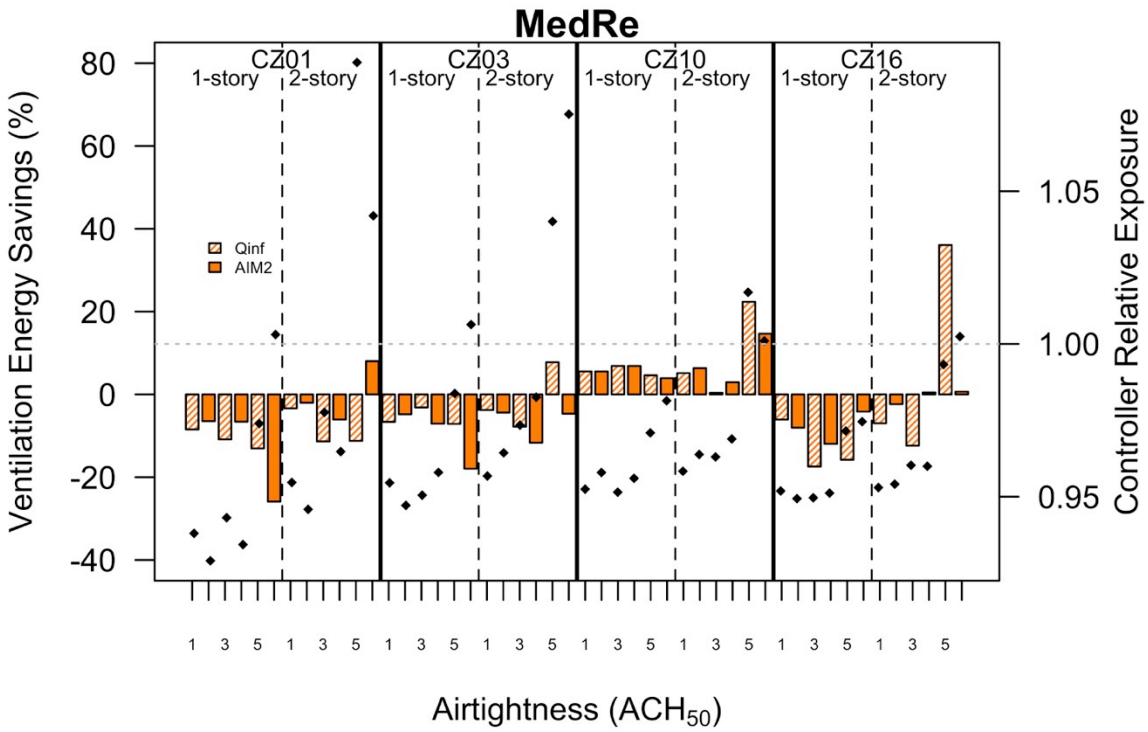


Figure 36 30-day running median TSVC ventilation energy savings.

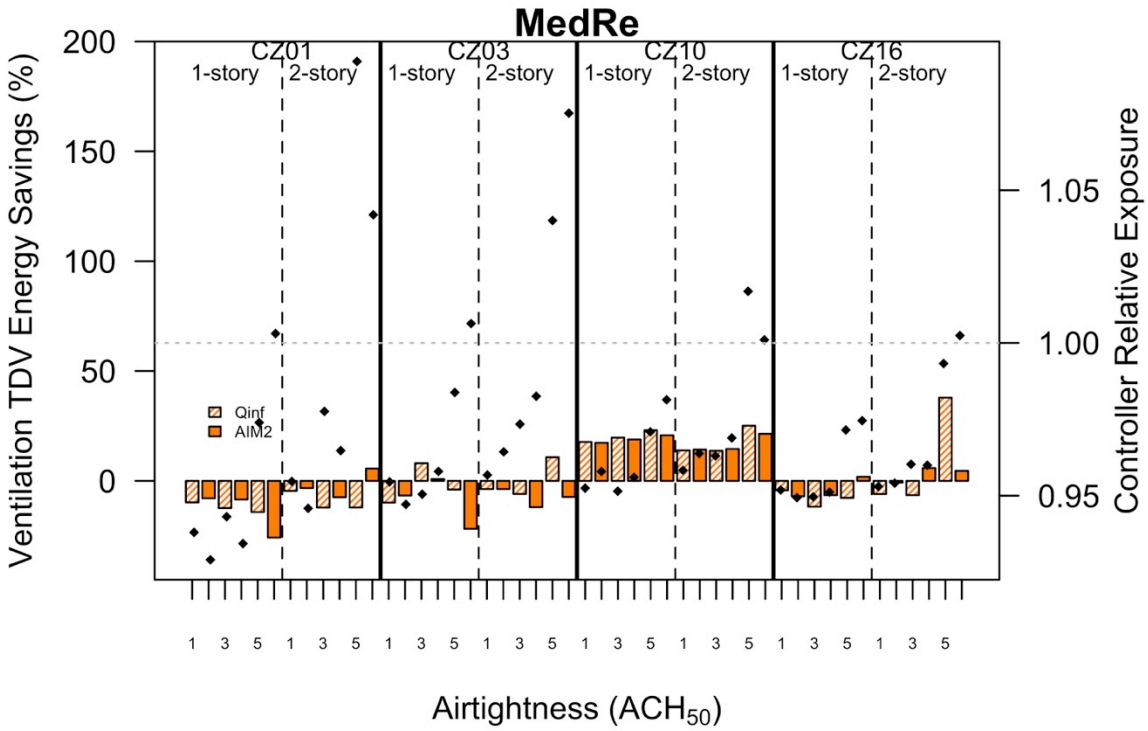


Figure 37 30-day running median TSVC ventilation TDV energy savings.

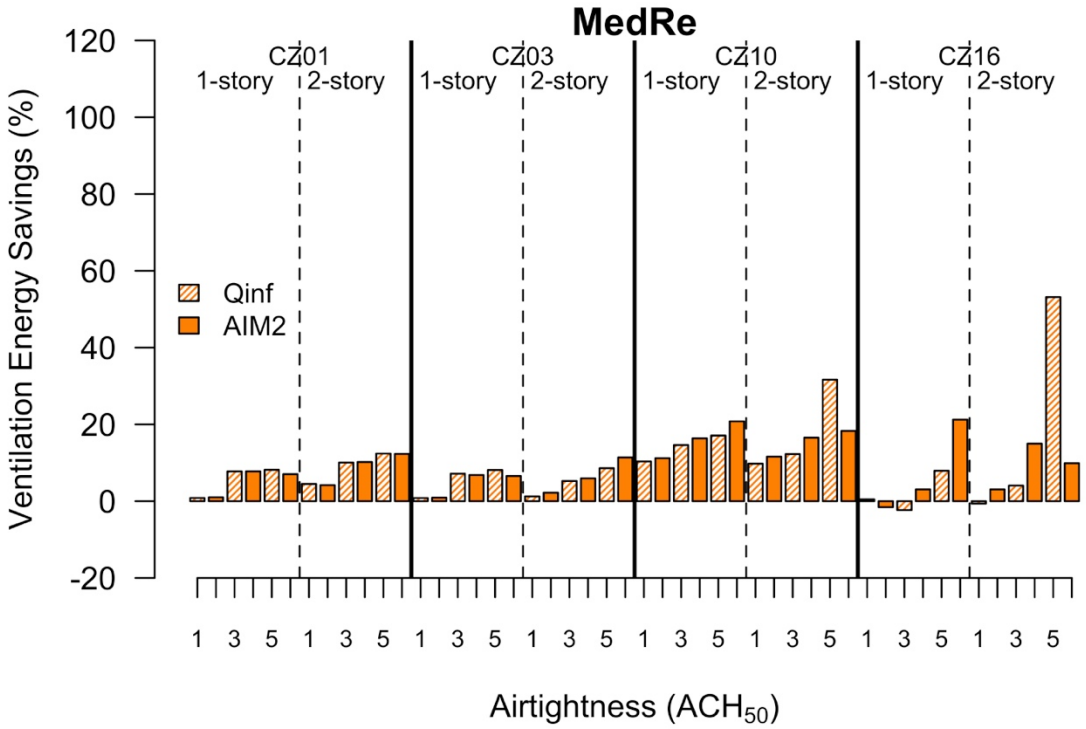


Figure 38 30-day running median TSVC normalized ventilation energy savings.

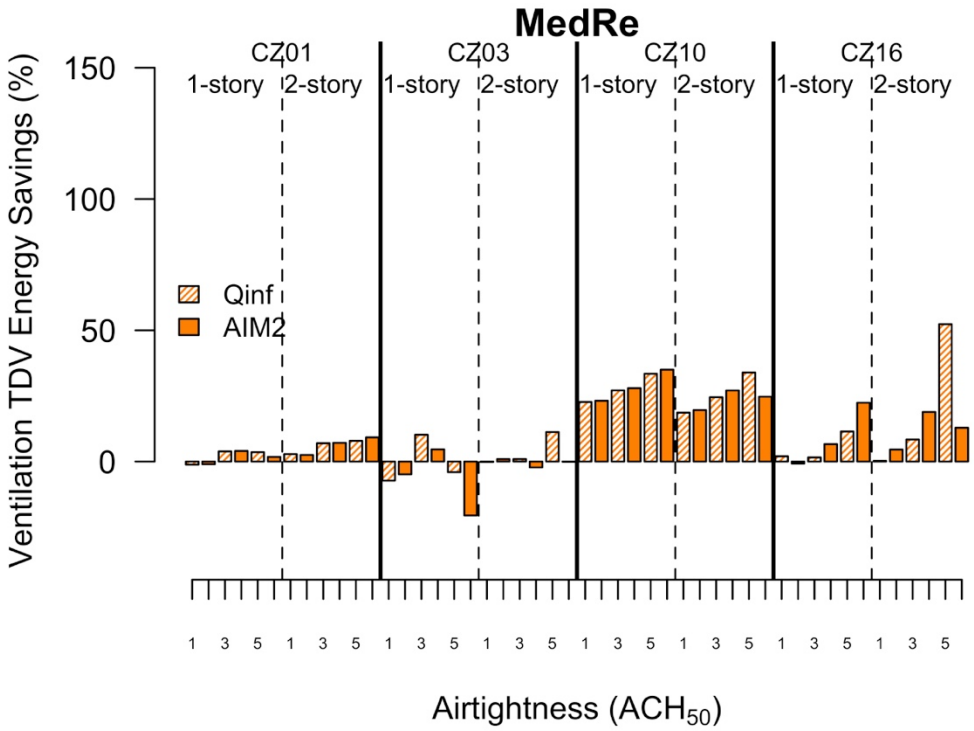


Figure 39 30-day running median TSVC normalized ventilation TDV energy savings.

We provide an example of the monthly controller exposure levels achieved by the 30-day Running Median TSVC for a 1-story medium 5 ACH_{50} prototype in CZ10 with a fan size multiplier of 2 (see Figure 40). Notably, the median exposure for each month is not equal to 1, which results from the inability of the prior month's 30-day running median to adequately predict the distribution of temperatures for the following month. So, the monthly values skew high and low by between 5-10%. Similarly, over the year, the annual average exposure (dotted green line) is above the target exposure of 1.0 (dashed blue line). An illustrative time-series example is provided to illustrate controller behavior in Figure 41.

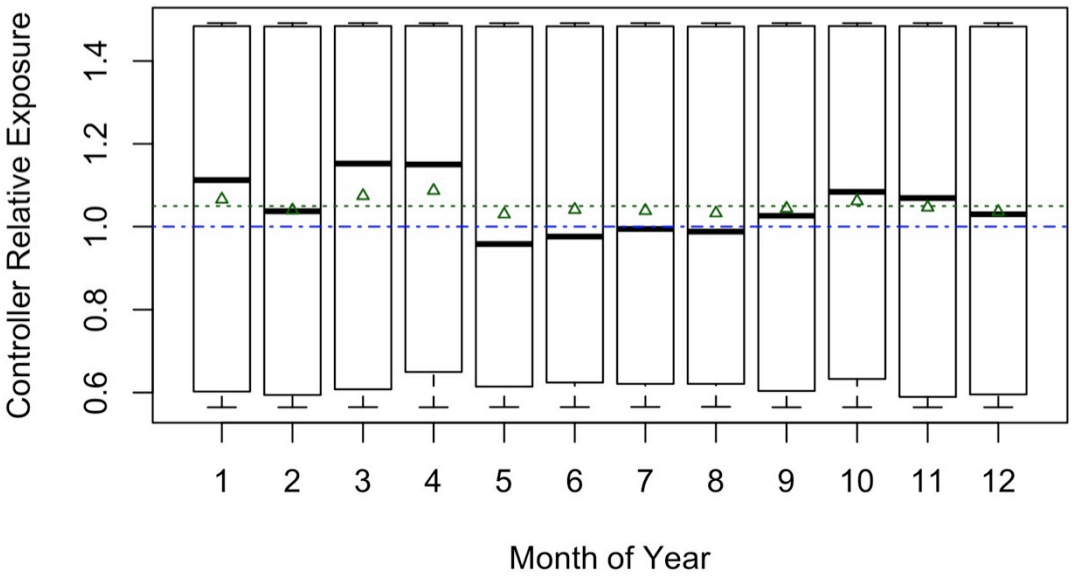


Figure 40 Monthly boxplot distributions of controller relative exposure for a 30-day Running Median example simulation in a 1-story medium 5 ACH_{50} prototype in CZ10 (Riverside). Blue dashed line is at 1.0 and the dotted green line is the annual average exposure achieved.

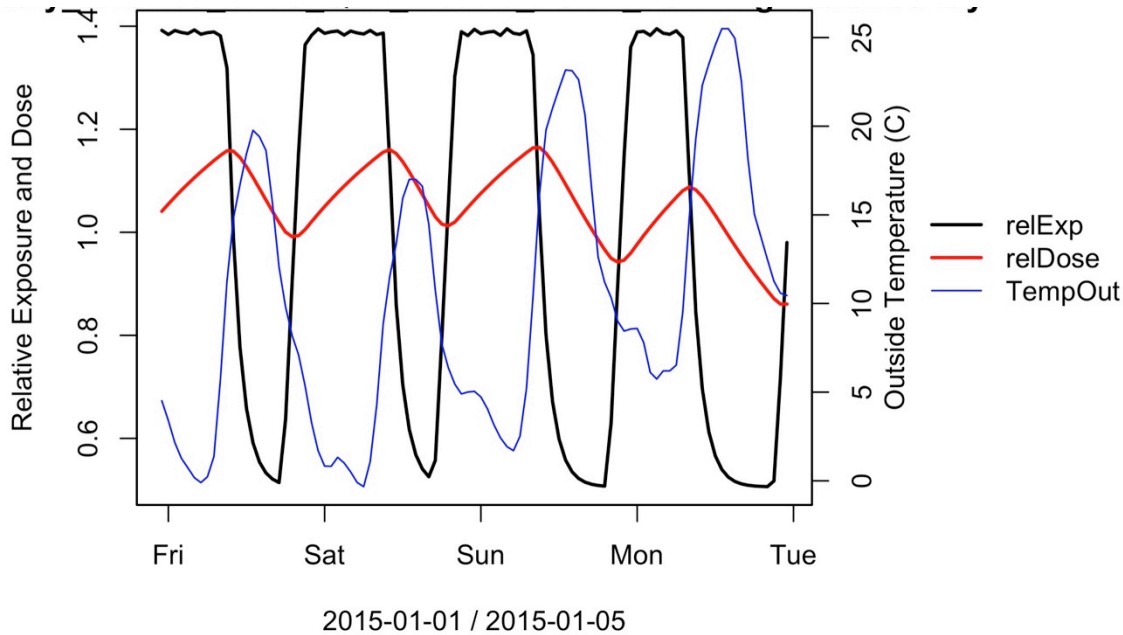


Figure 41 Example of the Running Median TSVC controller. 1-story medium, 3 ACH_{50} home in CZ10 with an FSM of 2. High RE target of 1.4 and low target of 0.5.

As noted above, we found that the running median controller was often not able to maintain equivalence with a continuous fan as designed per Appendix B. In general, we needed to reduce the high RE target (governing the amount of under-ventilation) by 0.2 in order to get annual exposure below one. The reason for this is that the relative exposure is a self-referencing time-series, and it takes time to travel between different values, such as a high and low RE target. It just so happens that in these cases, the controller consistently reaches and maintains the high RE target, while consistently not reaching the low RE target. The result is that you no longer get an average value of one or less. This is illustrated in the example Figure 2 for a 1-story 3 ACH_{50} home in CZ10. The controller consistently achieves and maintains the high RE target of 1.4, but when it increases ventilation to achieve the low target of 0.5, it hardly, if ever, reaches that target. This occurs because the exposure increases more rapidly when the fan is off than it is reduced when the fan is on. The net-effect is to skew the average exposure above one. This will occur to some extent in any cases where the controller cycles between high and low targets on a daily basis.

This inability to reach the low exposure target becomes more of an issue as the natural infiltration rate (Qing) predicted using ASHRAE 62.2-2016 equations increases relative to the target ventilation rate (Total). The reason for this is that our approach to fan over-sizing uses the Fan Size Multiplier (FSM), which is applied only to the 62.2 sized baseline ventilation fan. But the FSM is used in some control types as part of the control algorithm. For example, the target high and low exposure targets used in the running median control are FSM and 1/FSM, respectively. This approach works very well in a very airtight home, where the fan airflow is nearly equal to the whole house airflow. But in the leakier homes, the ventilation fan is only a fraction of the target ventilation rate, so doubling the fan

airflow fails to double the whole house airflow. These cases may never be able to achieve 1/FSM as an exposure target. Indeed, Figure 36 shows the controller exposure for the 30-day running median cases, and we see that the exposure is often above 1 for the 2-story 5 ACH_{50} cases. This results from the dynamics described in the prior paragraph, as well as in how the FSM is used to size fans and in the control algorithm itself.

5.3.3 Seasonal (Season)

For each case (combination of prototype, envelope leakage and climate) we show the Seasonal controller percent ventilation energy savings for site energy (Figure 42) and TDV (Figure 43) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 44) and TDV (Figure 45).

Overall, consistent raw savings were predicted with the Seasonal controller in nearly all climate zones and locations. Ventilation energy savings in most scenarios were roughly 20%, with select cases with increased consumption (in CZ3) and others with much higher savings (e.g., 2-story large homes with 5 ACH_{50} leakage in CZ10 and CZ16). There are no clear trends with envelope leakage or prototype, though the 2-story cases have marginally higher savings in some scenarios. The infiltration accounting method is again inconsistent in its effects. The AIM-2 method gives some benefit in CZ10 and 16, while the Qing approach is slightly better in CZ3. Relative exposure (the black diamonds) was very well controlled to the target of 0.97 in nearly all cases. The exceptions were the 2-story 5 ACH_{50} cases, where the noted issue about using the Fan Sizing Multiplier in the control algorithms increased average exposure, because the whole house airflow could not reach a level corresponding with the 1/FSM low exposure target. Notably, this effect is small. When this controller fails to meet the exposure below one requirement, it does so with annual average exposure at most of 1.04.

The raw TDV savings for each case show a strong increase in ventilation TDV energy use in CZ10 (Riverside), which is a cooling dominated location in terms of TDV energy, due to its high electrical cooling loads. The Seasonal controller increases the ventilation rate during the cooling season, in an attempt to reduce heating energy, while sacrificing somewhat higher cooling loads. In most locations, this still results in net-TDV savings, but in cooling-dominated locations, the TDV electricity penalty outweighs heating season benefits. In these cooling climates, TDV ventilation energy increased 20-50%.

Normalized ventilation percent savings are increased across the board, with clear trends towards greater percent savings in homes with leakier envelopes. The trend towards improved performance when using AIM-2 in CZ10 and 16 is clearer when normalized, as is the benefit of the Qing approach in CZ3. The 2-story prototypes have much higher savings in the leakiest cases, reaching savings in the range of 50-100%. When normalized, TDV energy use still increases in all CZ10 cases, due to the

shift of ventilation airflows to the cooling season. CZ16 shows consistent normalized TDV energy savings with the Seasonal control, with increasing savings in leakier, 2-story cases using the AIM-2 infiltration model. The normalized TDV savings are erratic in CZ3, following no clear patterns.

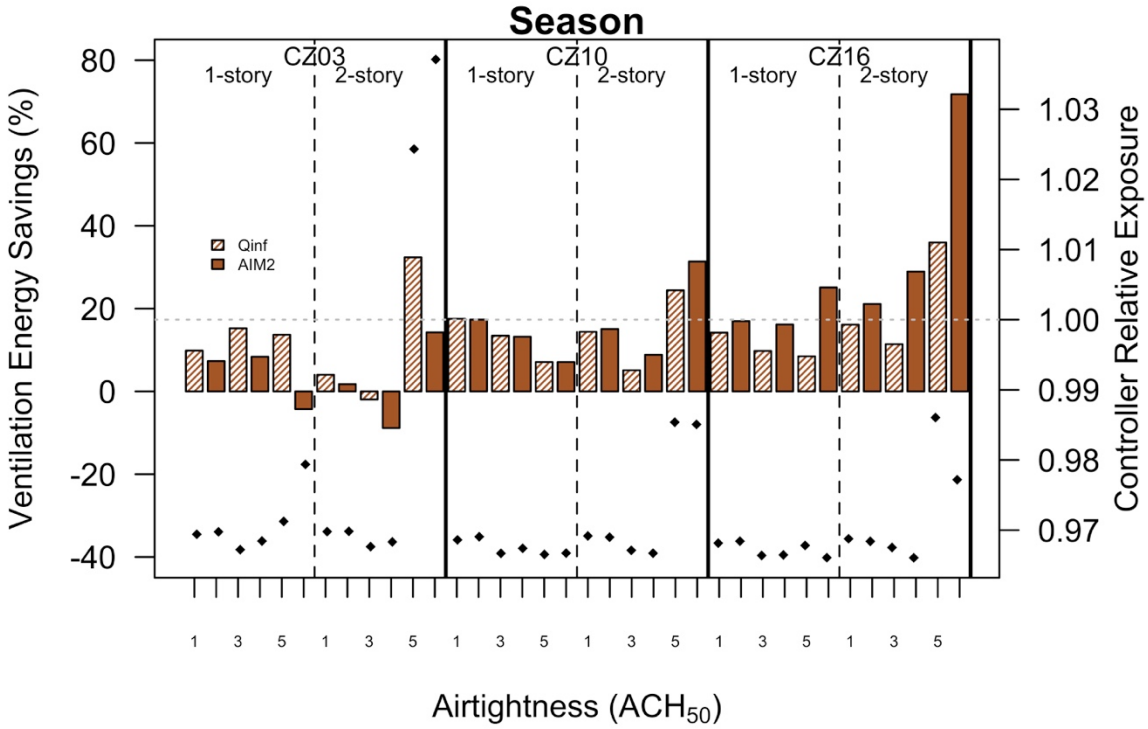


Figure 42 Seasonal TSVC ventilation energy savings. No cases simulated in CZ1, due to lack of cooling season.

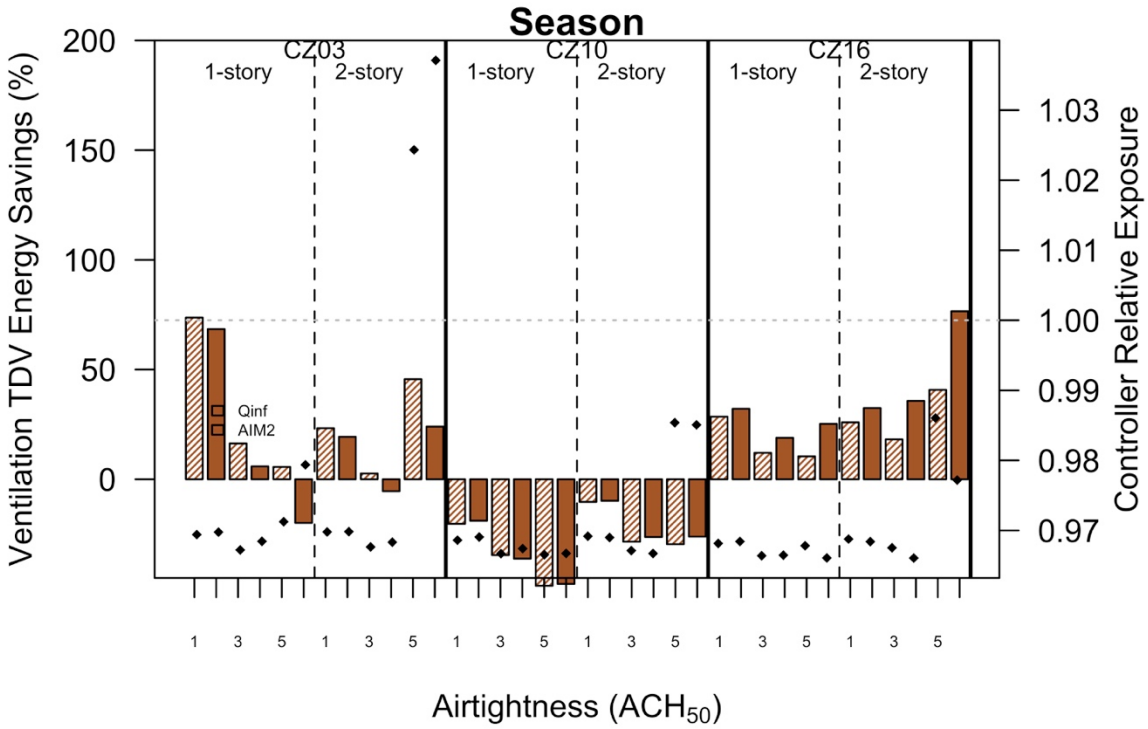


Figure 43 Seasonal TSVC ventilation TDV energy savings. No cases simulated in CZ1, due to lack of cooling season.

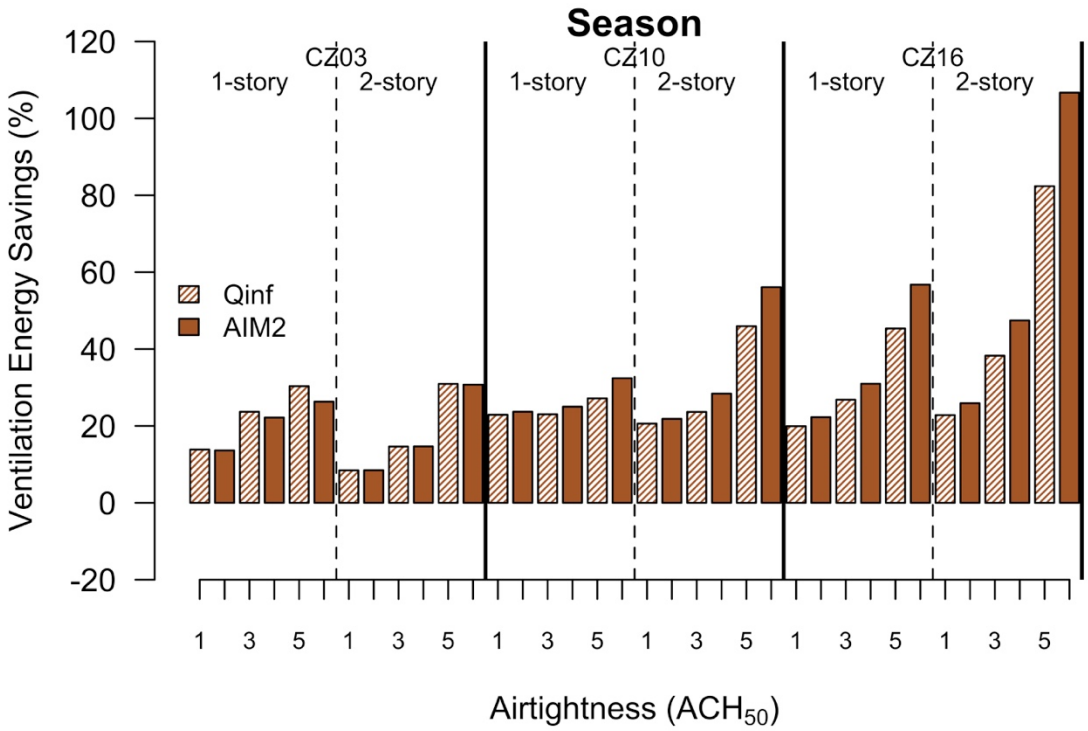


Figure 44 Seasonal TSVC normalized ventilation energy savings. No cases simulated in CZ1, due to lack of cooling season.

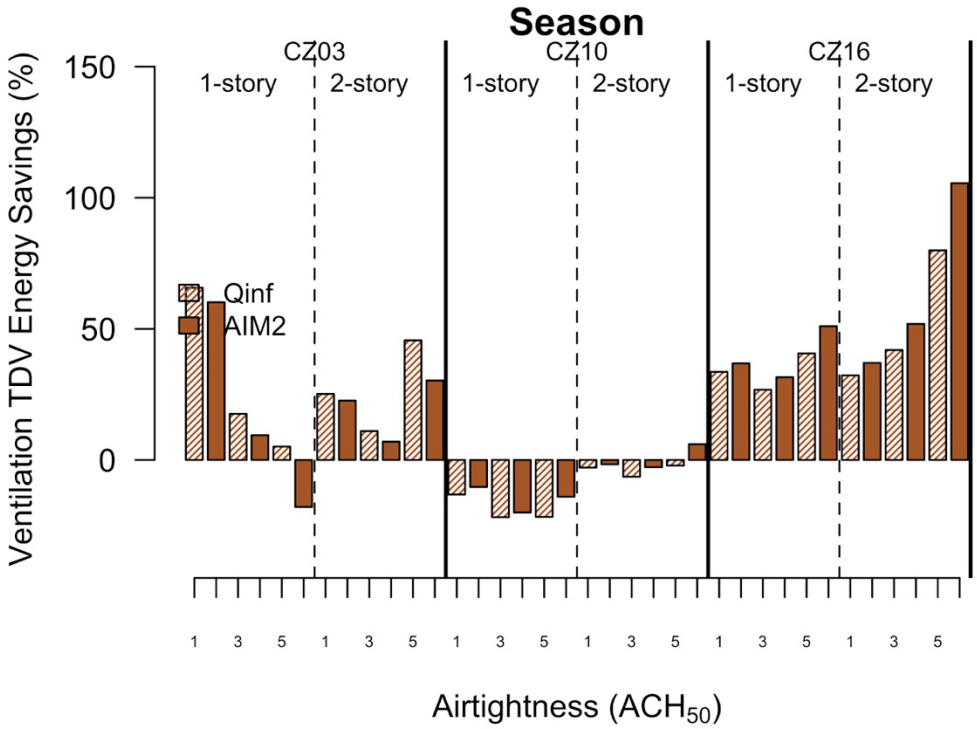


Figure 45 Seasonal TSVC normalized ventilation TDV energy savings. No cases simulated in CZ1, due to lack of cooling season.

We illustrate the simple and consistent operation of this TSVC using daily minimum, mean and maximum controller exposure values in Figure 3. This example case is a 1-story medium 5 ACH_{50} prototype in CZ10, heating season exposure target of 1.5 and cooling season target of 0.61. When in heating season, the 1.5 target is consistently maintained, with very little variability over the course of a day; same for the cooling season at the low exposure target. This predictable behavior ensures relatively straightforward estimation of the annual average exposure during design phase.

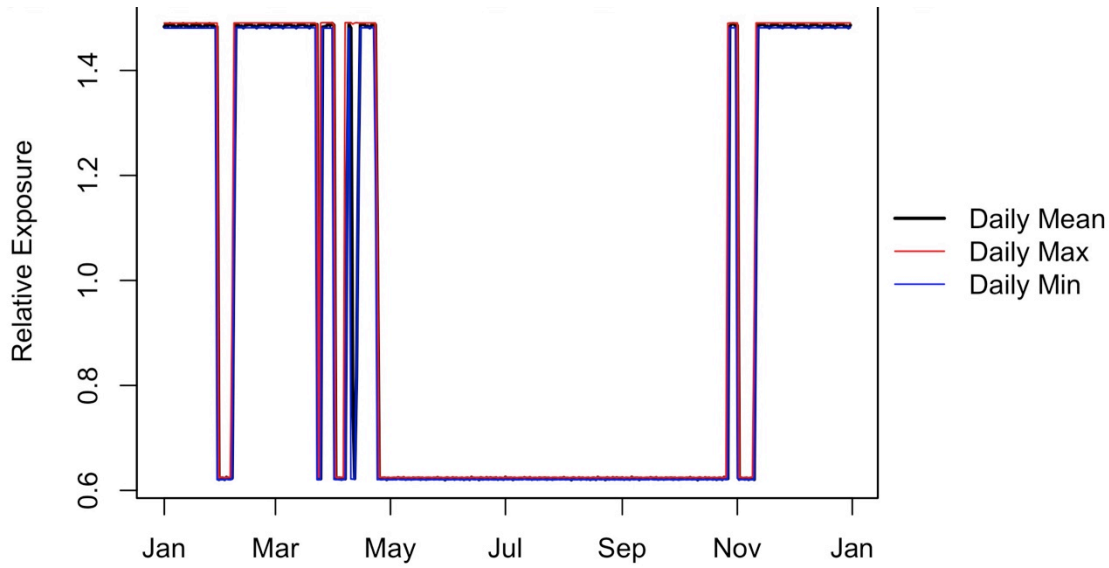


Figure 46 Seasonal TSVC illustration of daily minimum, mean and maximum values for controller relative exposure. 1-story medium 5 ACH50 homes in CZ10 with heating season RE target of 1.5 and cooling season target 0.61.

5.3.4 Optimized Cut-Off (CutOff)

For each case (combination of prototype, envelope leakage and climate) we show the CutOff controller percent ventilation energy savings for site energy (Figure 47) and TDV (Figure 48) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 49) and TDV (Figure 50).

The cutoff control was able to maintain equivalence and save ventilation energy in the majority of cases, with savings between 30 and 80% of ventilation site energy in CZ10 and 16. Savings worsened with increasing envelope leakage in CZ1, and savings improved with leakage in CZ16. CZ 3 and 10 showed unclear patterns with envelope leakage. As with the Seasonal controller, the AIM-2 infiltration model improved savings in CZ10 and 16, while the Qing model gave better savings in CZ3. The 2-story homes had greater savings in CZ16, but prototype effects were otherwise mixed. Performance remained solid for raw TDV ventilation energy savings in CZ10 and 16, but TDV savings in CZ3 improved greatly, with savings in the 30 to over 100% range. As with most controllers, its performance was poor in CZ1 homes.

The normalized site and TDV energy savings were improved across the board. Again, when normalized, increased envelope leakage clearly was associated with increased normalized percent savings. Similarly, the AIM-2 infiltration model improved performance in CZ10 and 16, and Qing was best in CZ3 cases. Prototype effects were concentrated in CZ16, where the 2-story cases saved much more

normalized energy. Normalized TDV savings generally averaged in the range of 50% across CZ3, 10 and 16.

In addition to good energy performance, the CutOff TSVC has the further benefit that the peak exposure experienced by the occupants is much lower (see Figure 79), generally just a few tenths above the seasonal average exposure target.

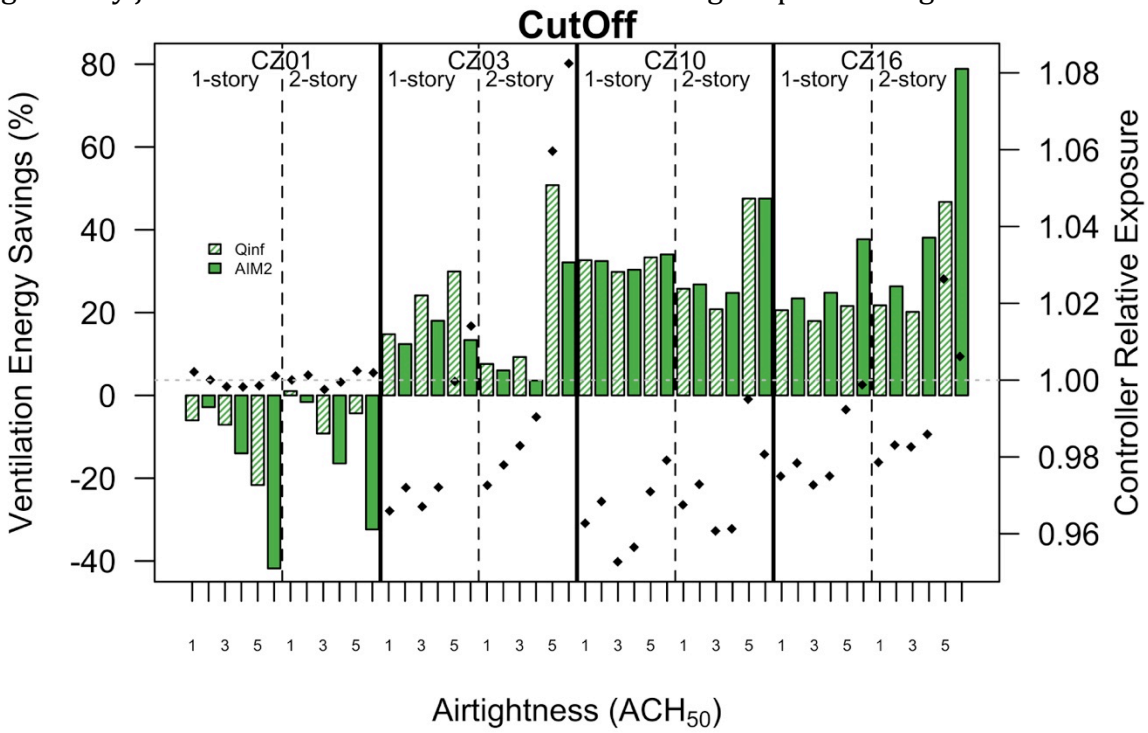


Figure 47 Cutoff TSVC ventilation energy savings.

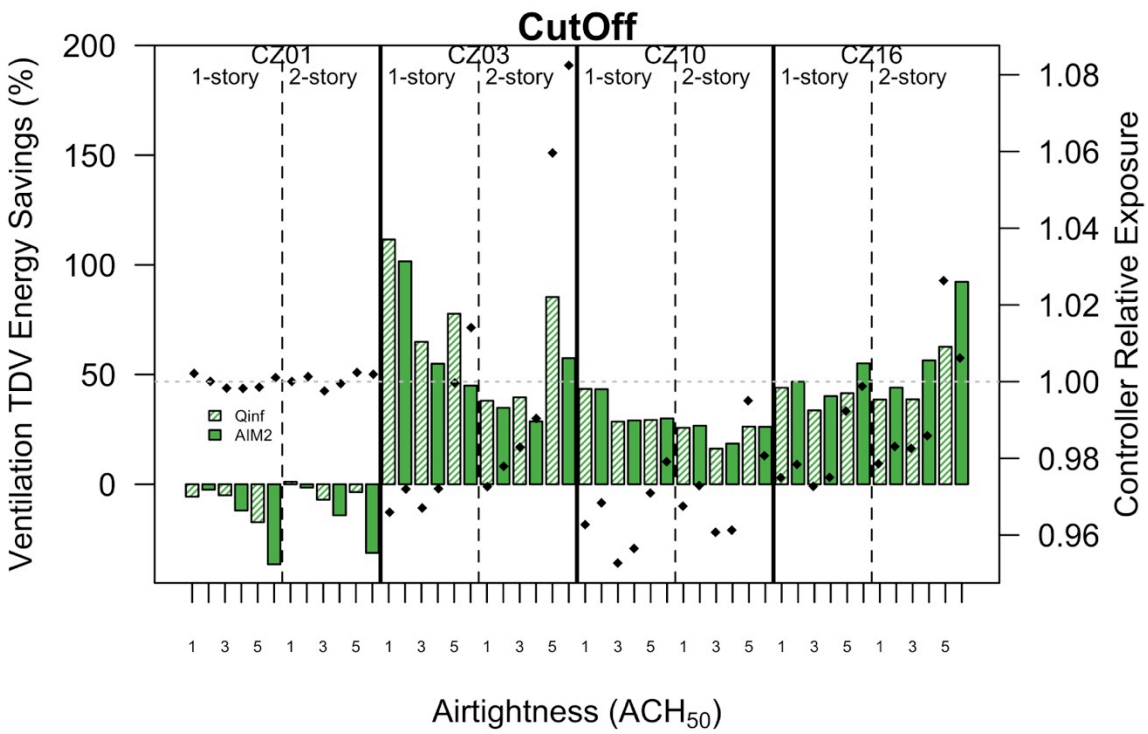


Figure 48 Cutoff TSVC ventilation TDV energy savings.

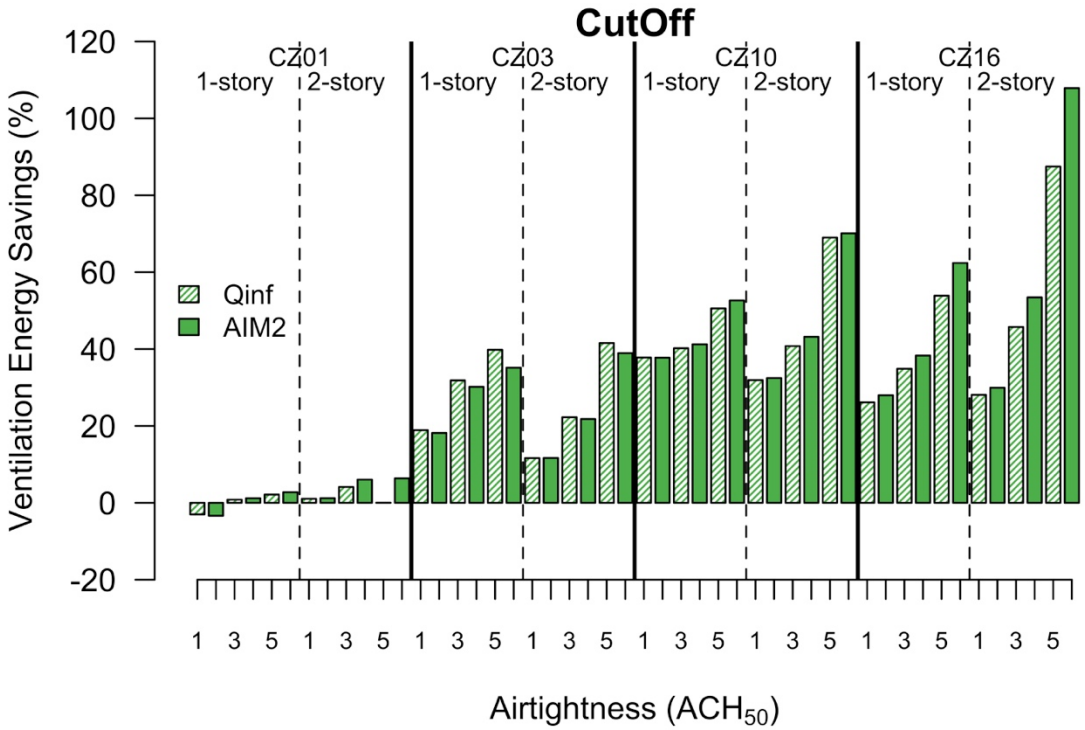


Figure 49 Cut-Off TSVC normalized ventilation energy savings.

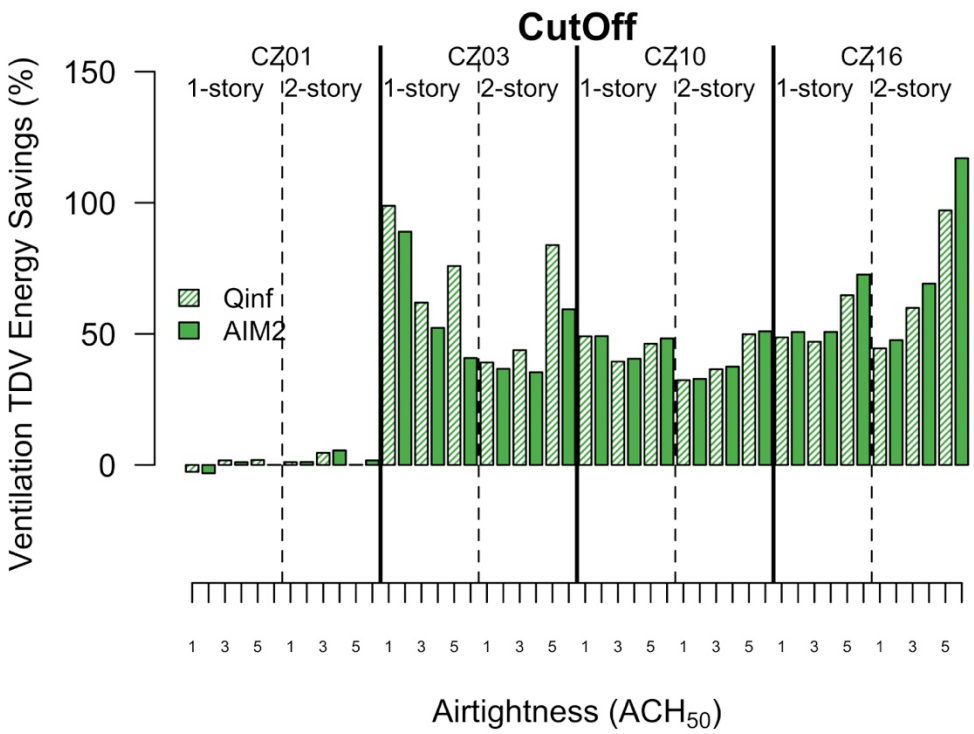


Figure 50 Cut-off TSVC normalized ventilation TDV energy savings.

The monthly distribution of controller exposure is shown for an example case in Figure 51 for a 1-story 1 ACH_{50} home in CZ10. Heating season mean exposure target was 1.5 and cooling season was 0.62, and the green triangles show monthly means. Here we see the clear pattern of increasing exposure (reducing ventilation) during the heating months and reducing exposure (increasing ventilation) during the cooling season. The monthly averages align pretty well with the seasonal targets, and the peak exposure values are well controlled to the limits of 1.8 in heating and 1.16 in cooling.

A time-series illustration of this same exact case is provided in Figure 52 with controller exposure, dose and outside temperature (dashed green line represents the heating season temperature cutoff for increased exposure). We see that during the heating season, the controller steadily maintains the peak exposure target of 1.8 unless the outside temperature exceeds 16.7°C, at which point the controller increases ventilation and targets exposure of 1/FSM (0.5 in this case). This successfully reduces ventilation for the maximum amount of time, while still keeping the annual average exposure below one.

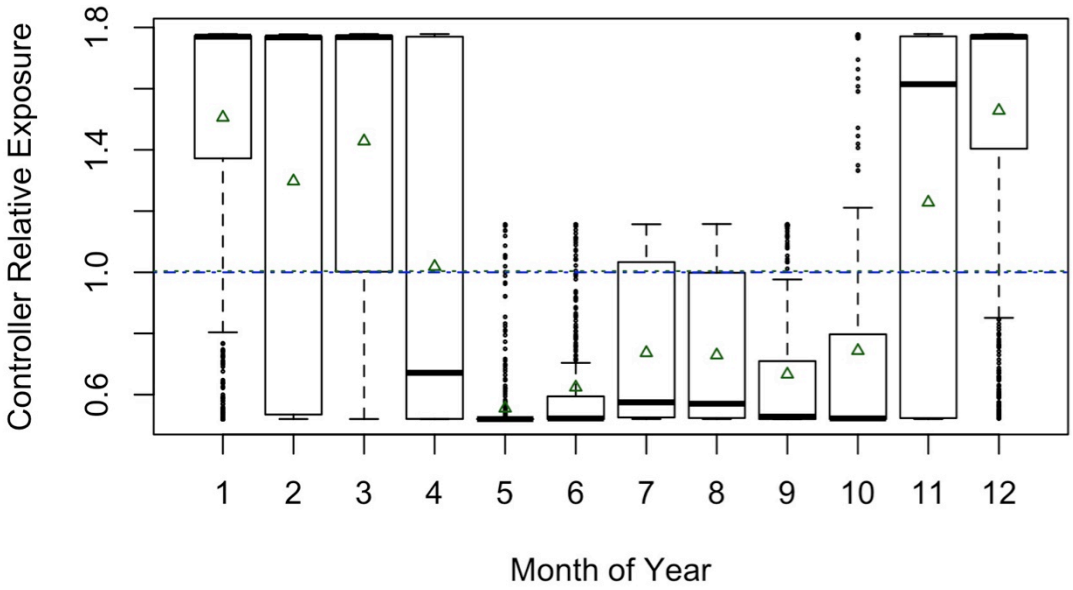


Figure 51 Monthly boxplot distributions of controller relative exposure for the Cutoff TSVC in a 1-story 1 ACH_{50} home in CZ10. Heating season mean exposure target was 1.5 and cooling season was 0.62. Green triangles show monthly mean.

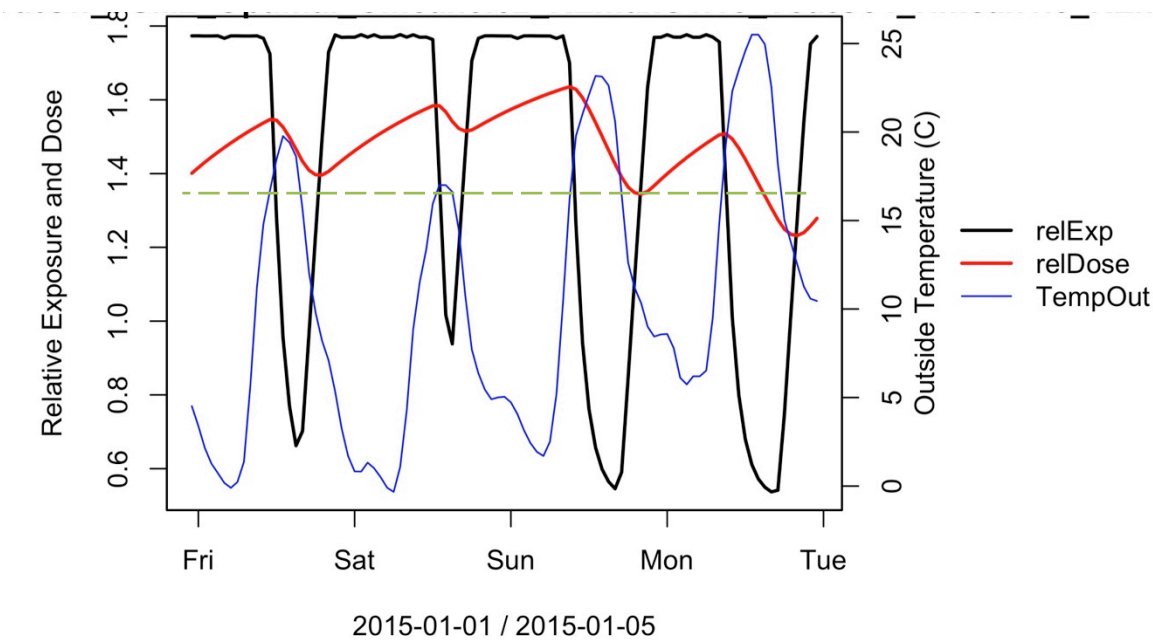


Figure 52 Time-series illustration of Cutoff TSVC controller exposure, dose and outside temperature in a 1-story 1 ACH_{50} home in CZ10. Low exposure target (high ventilation rate) is targeted when outside temperature (blue line) exceeds 16.7°C (dashed green line).

5.3.5 Variable Airflow (VarQ)

For each case (combination of prototype, envelope leakage and climate) we show the VarQ controller percent ventilation energy savings for site energy (Figure 53) and TDV (Figure 54) using the raw simulation outputs. We then show the same

results when normalized by relative exposure for site energy (Figure 55) and TDV (Figure 56).

On average, the VarQ TSVC has the largest ventilation energy savings, for both site and TDV energy use at roughly 40 and 60% weighted average savings, respectively. It also had among the highest peak cooling demand savings, shedding between 0 and 400 watts during the 2-6pm peak period on the hottest days of the year. This controller reduced occupant exposure and improved IAQ in nearly all cases relative to the baseline continuous fan. The VarQ controller had by far the highest peak exposures, because it allowed the IAQ fan to be completely turned off during some outdoor conditions. The peak exposures could be drastically reduced, by setting a minimum target airflow of 5 L/s instead of 0 L/s. The VarQ controller also suffered from relatively more cases that failed to meet the annual exposure requirement, with roughly 30% failure rate vs. roughly 20% for some of the other well-performing controllers. That being said, when it failed, the VarQ generally exceeded 1.0 by only 1-5%, well within the range achieved by the continuous baseline IAQ fans. Relative to the VarRe or CutOff controllers, the VarQ controller also requires more user inputs in order to generate the optimum control parameters. This makes specification of the controller more complex and variable with house parameters, such as airtightness, climate zone, etc.

Raw percent site savings were greatest in CZ10, with consistent savings levels across envelope leakages and infiltration assumptions. Aside from climate zone, house prototype was clearly an important determinant of VarQ performance, with greater savings in the 1-story prototypes, in both CZ10 and 3. Raw percent TDV savings were also greater in 1-story prototype homes and otherwise varied little across envelope leakage levels and infiltration assumptions. Notably, the controller exposure was well below 1.0 in several of the CZ16 cases. Even when below 0.90 the energy savings were indistinguishable from similar cases with exposures near 1.0.

When normalized by relative exposure, the site and TDV savings all increased substantially. This was the first control type to show meaningful energy savings in CZ1, when normalized. As with other controls, when normalized, the percent savings increased with envelope leakage, infiltration model assumptions had little impact, and prototype performance was similar, with the exception of the leakiest cases in CZ16, where 2-story savings were substantially larger than in 1-story. This is notable, because the raw savings were stable across leakage levels, and normalization introduced clear differences with leakage. Normalized TDV percent savings were sometimes flat across leakage levels (CZ3) and other times followed the familiar pattern (CZ16). It could be that the increasing savings with increasing envelope leakage has more to do with normalization of the baseline cases, rather than of the control cases. The baselines have clear patterns of higher exposure in leakier homes, due to superposition fan sizing models used in 62.2-2016 (see Appendix R). So, smart control savings may be increasing with leakage, because the

baseline case energy consumption consistently increases when normalized, which increases the apparent savings.

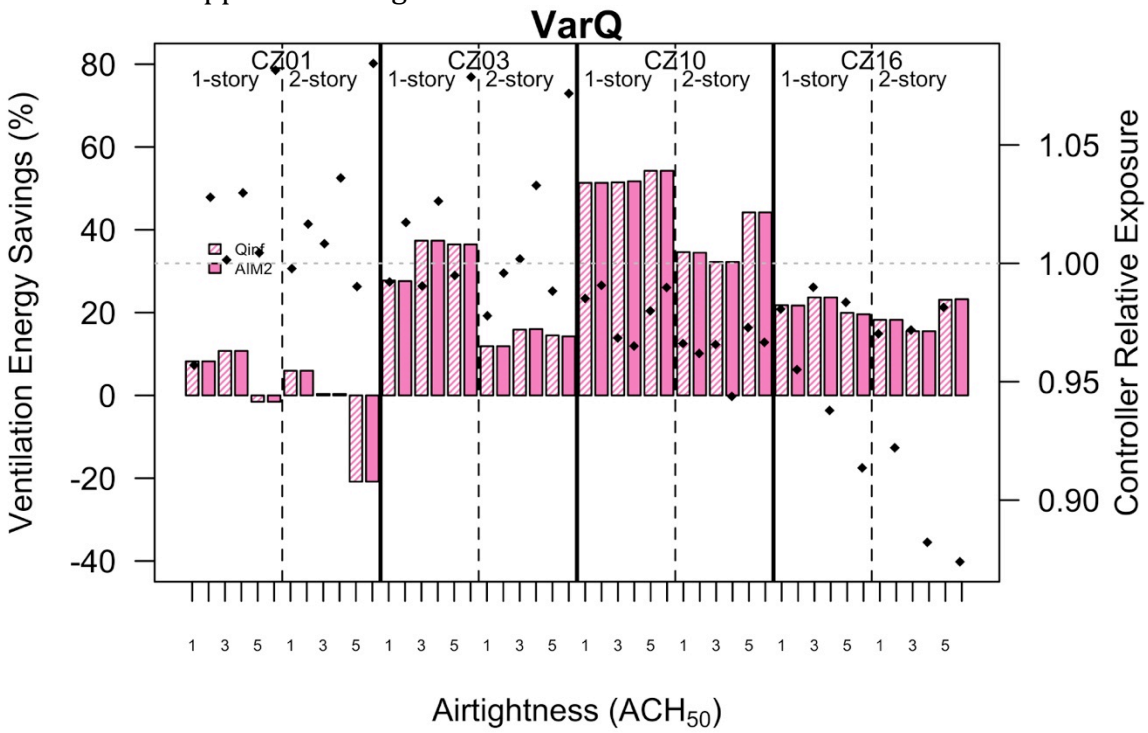


Figure 53 Variable airflow TSVC ventilation energy savings.

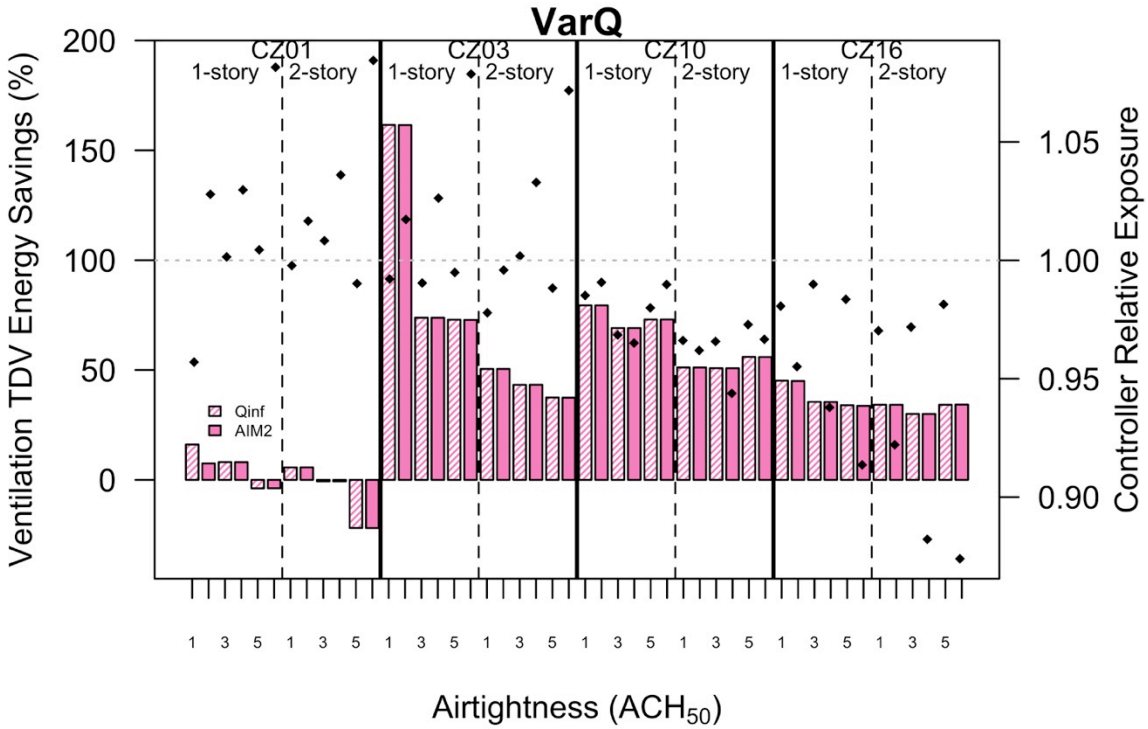


Figure 54 Variable airflow TSVC ventilation TDV energy savings.

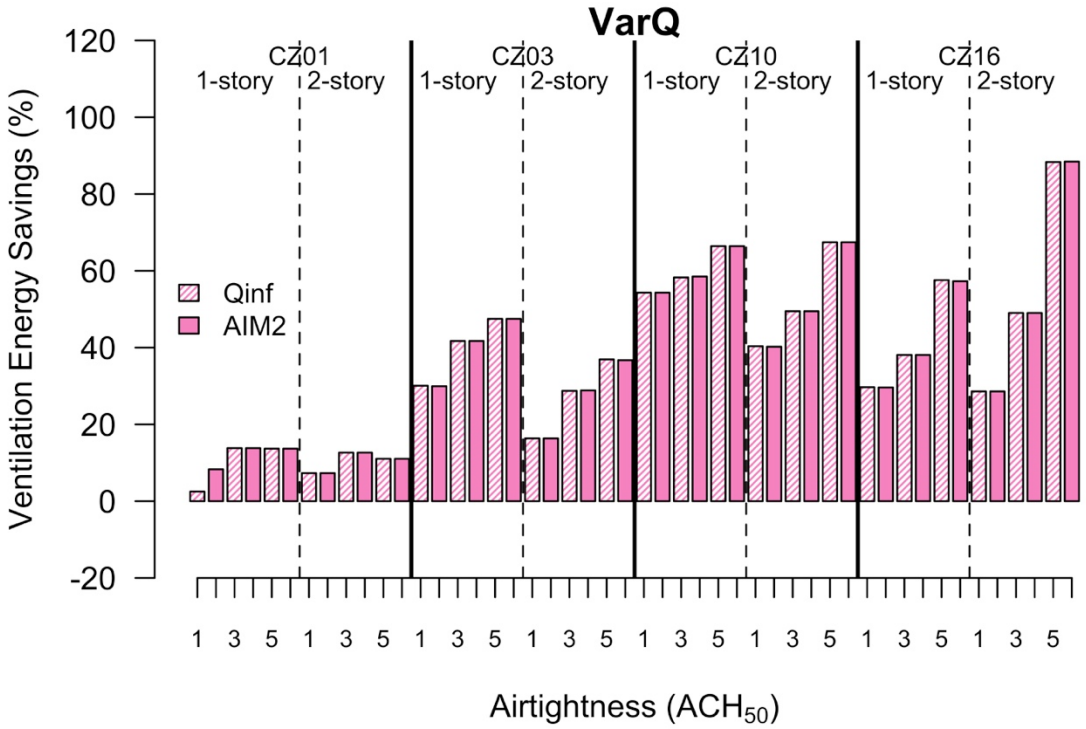


Figure 55 Variable airflow TSVC normalized ventilation energy savings.

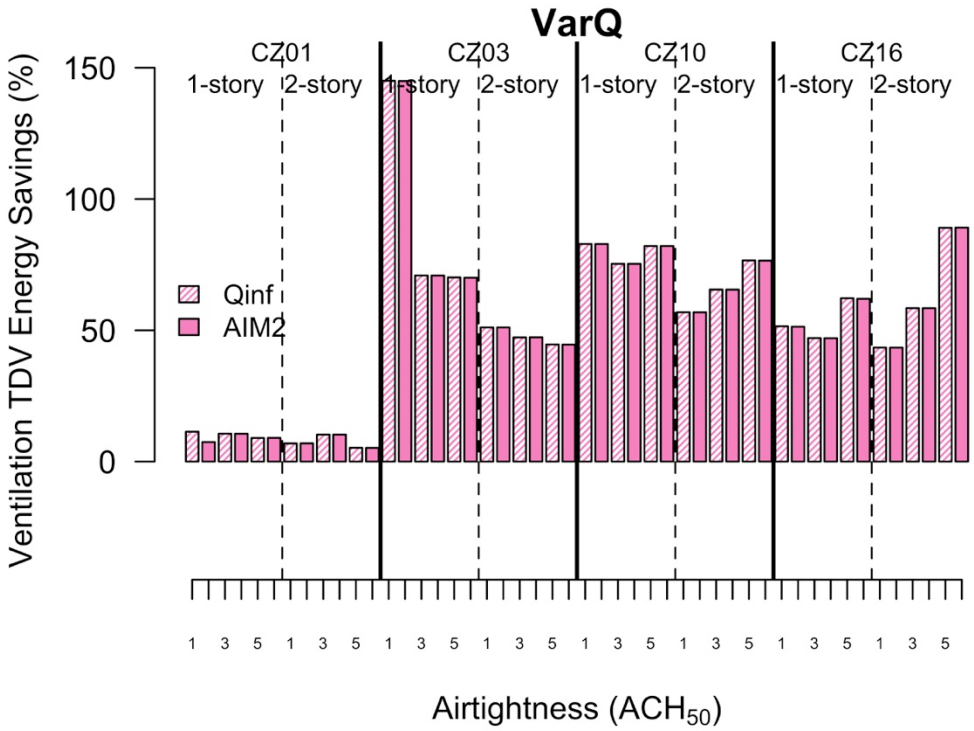


Figure 56 Variable airflow TSVC normalized ventilation TDV energy savings.

The VarQ controller also does the most seasonal shifting of ventilation, with the highest average exposure values in heating periods and cooling periods. The monthly distributions of controller exposure are plotted for an example case of the VarQ controller in Figure 57, for a 1-story 5 ACH_{50} home in CZ16 (Blue Canyon). The monthly controller exposure values are fairly high. Even for similar monthly average exposures (as in the Cutoff controller in Figure 51), the VarQ allows much higher peak exposures during most months of the year.

An illustrative example time-series plot is provided to shown VarQ controller behavior in Figure 58 for a 1-story 5 ACH_{50} home CZ10 (Riverside) with a fan size multiplier of 2. This plot shows the real and controller estimates of relative exposure, along with the house airflow and outside temperature. We see that for most hours of the day, the VarQ controller keeps the house airflow at a low number, with minimal fan airflow and some infiltration. When the outside temperature increases, the IAQ fan airflow ramps up proportionally until it is at full airflow around 80 L/s.

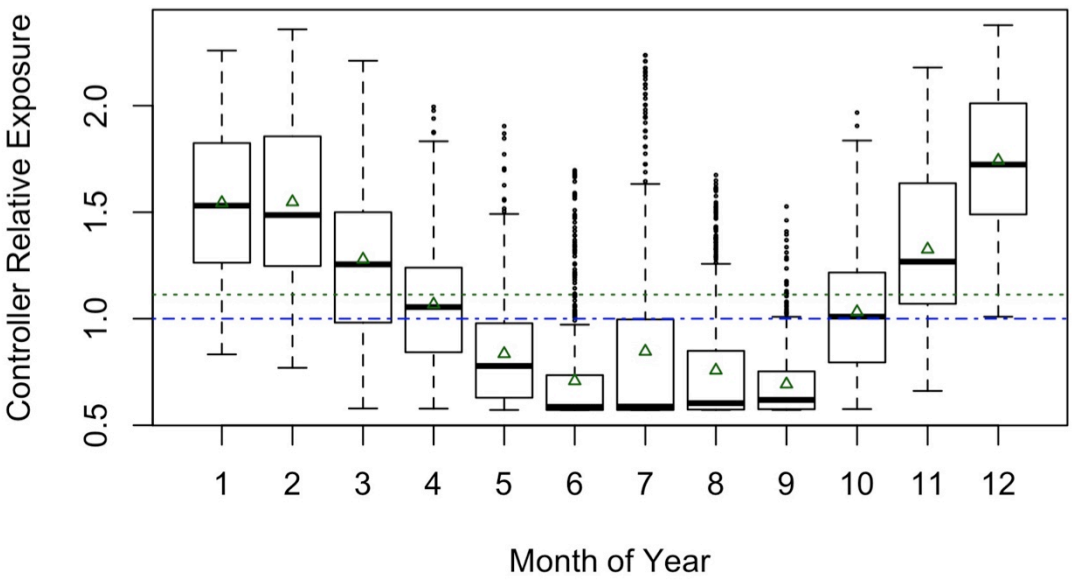


Figure 57 Monthly distributions of controller relative exposure for the VarQ TSVC controller in a 1-story 5 ACH_{50} home in CZ16 (Blue Canyon). Blue dashed line is the target annual exposure and the dotted green line is the actual average exposure.

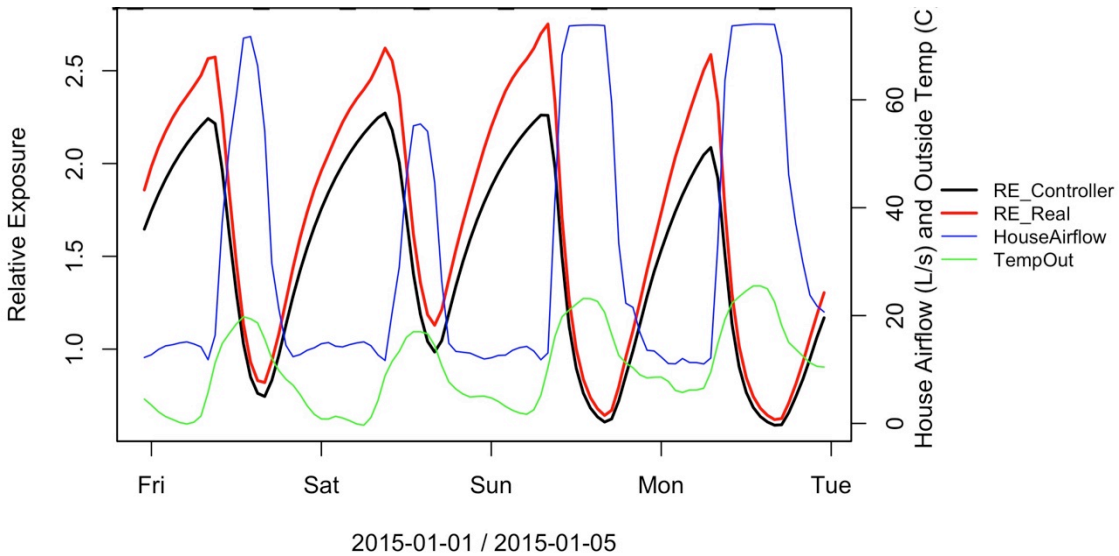


Figure 58 Time-series illustration of the VarQ controller in a 1-story 5 ACH_{50} home in CZ10 (Riverside), including controller and real exposure, along with house airflow and outside temperature.

5.3.6 Variable Exposure Target (VarRe)

For each case (combination of prototype, envelope leakage and climate) we show the VarRe controller percent ventilation energy savings for site energy (Figure 59) and TDV (Figure 60) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 61) and TDV (Figure 62).

Similar to the VarQ TSVC, the VarRe controller performed very well across climate zones and house types. Site ventilation savings are in the 20-50% range, while TDV savings range from 45-80% (an up to 150% in two cases). The TDV savings are quite consistent across climate zones 3, 10 and 16. CZ3 and 16 show improved raw site savings when envelope leakage increases (and worsened savings in CZ1), while savings in CZ10 are flat across leakage levels. Again, the AIM-2 infiltration model has obvious performance benefits in CZ10 and 16, while performance in CZ3 is improved using the Qinf infiltration assumption. Prototype has little impact on the raw percent site savings.

Again, the ventilation percent savings are improved when normalized by exposure. As with VarQ, the VarRe control was able to achieve meaningful savings in CZ1 when normalized to ensure the same IAQ. Again, normalized site energy savings clearly increase with envelope leakage, and the other patterns are similar to those described for the prior control strategies.

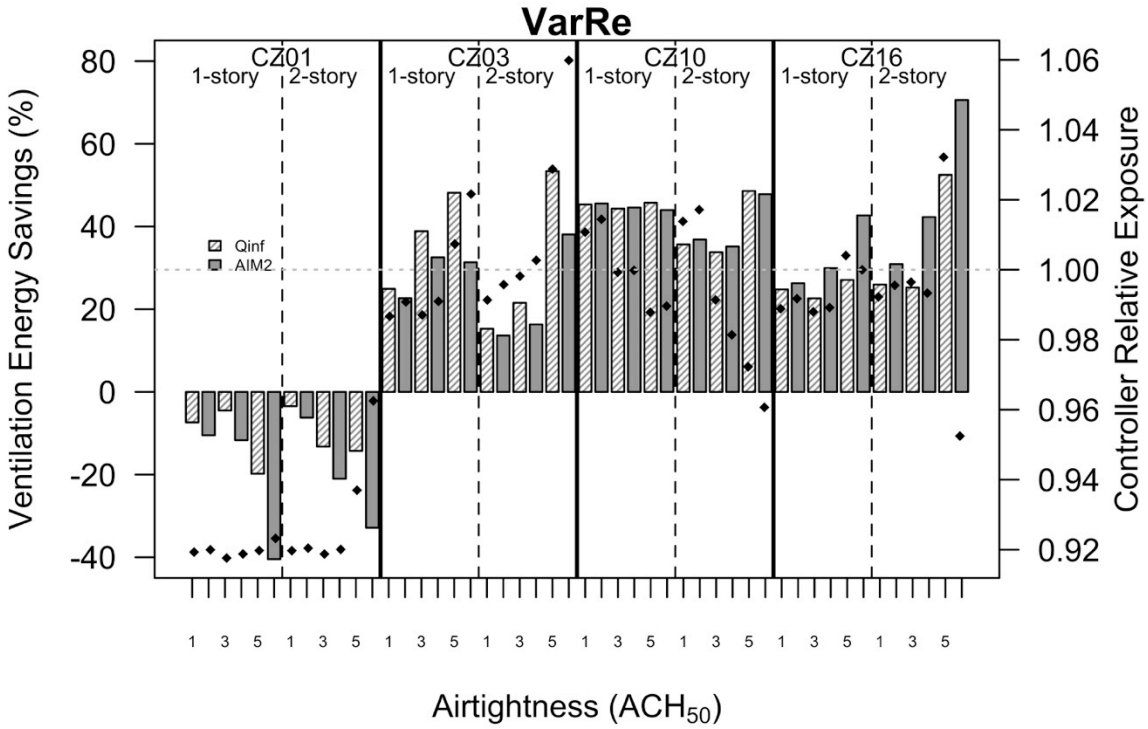


Figure 59 Variable exposure TSVC ventilation energy savings.

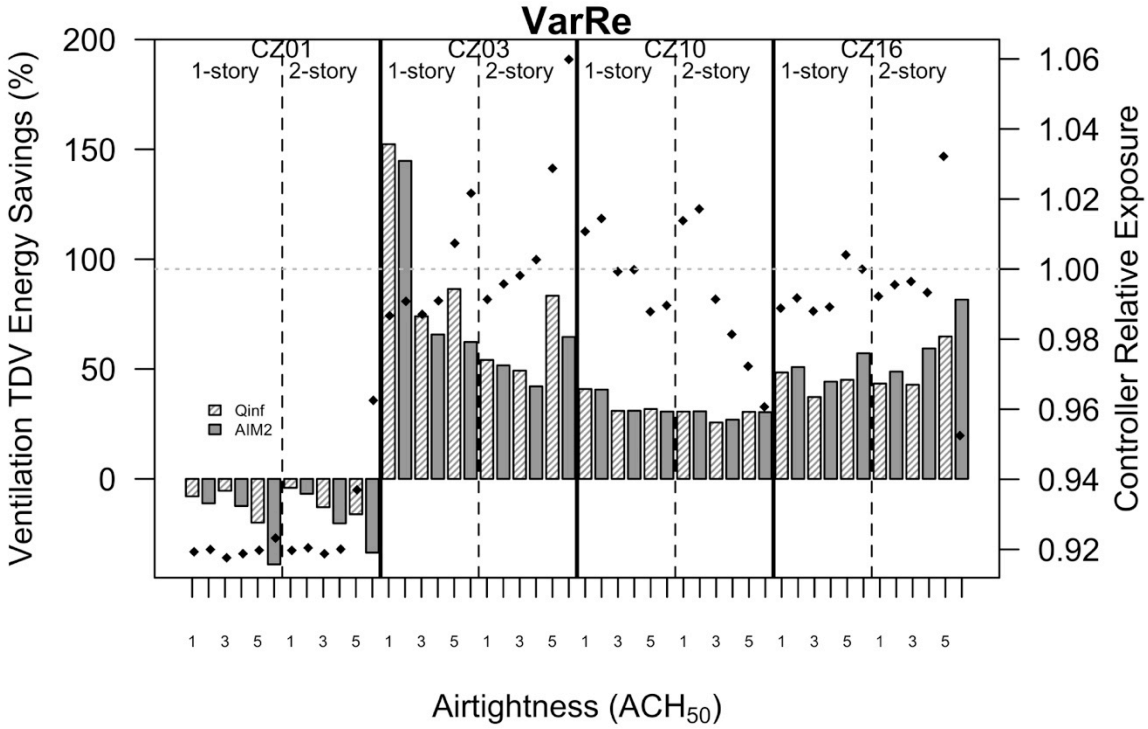


Figure 60 Variable exposure TSVC ventilation TDV energy savings.

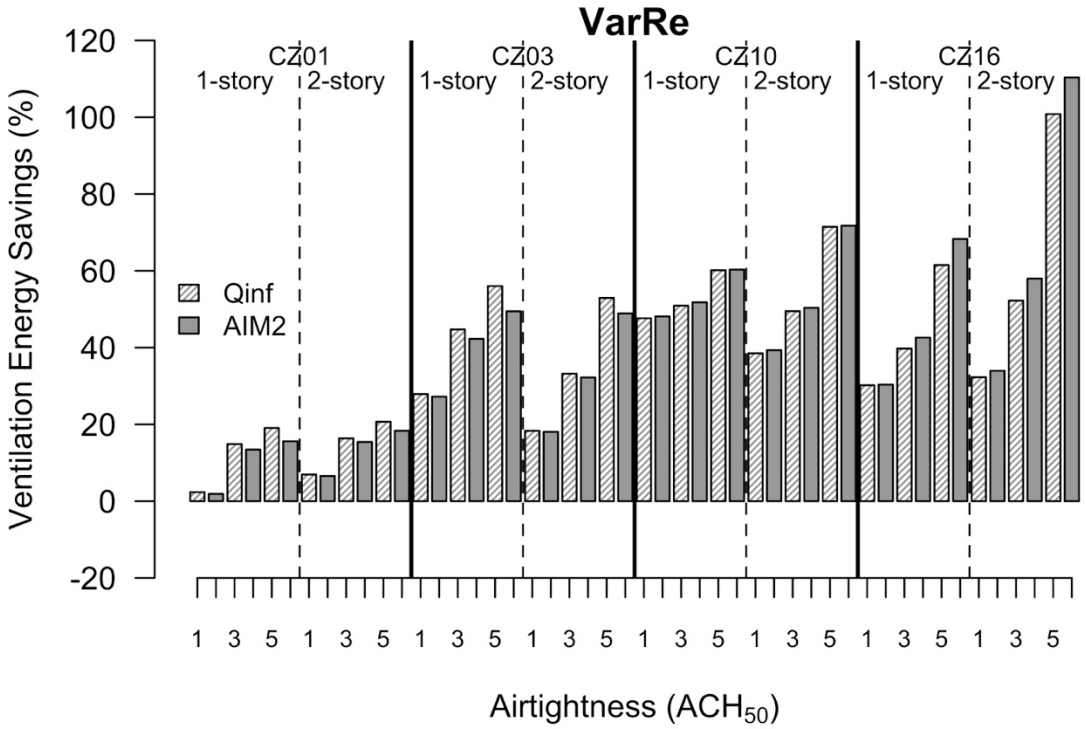


Figure 61 Variable exposure TSVC normalized ventilation energy savings.

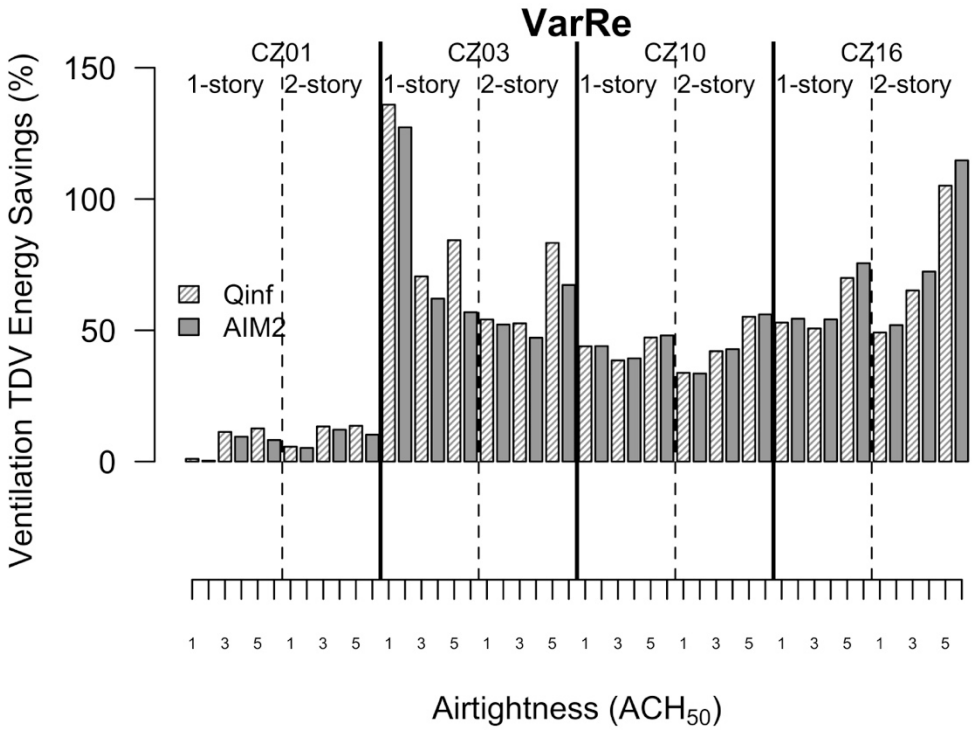


Figure 62 Variable exposure TSVC normalized ventilation TDV energy savings.

The monthly distribution of controller exposure values (Figure 63) for the VarRe controller is very similar to that used for the VarQ TSVC. Exposure and ventilation are shifted seasonally, with high exposure and low airflow during the heating months and vice versa during cooling periods. The peak exposure values are lower in the VarRe than in the VarQ, because the fan is never just turned off, rather a high exposure value maintains a low ventilation rate.

An example time-series plot is also provided to show controller behavior in Figure 64 for a 1-story 1 ACH_{50} home in CZ10 with a peak heating season exposure target of 4.1 (unusually high). We see that the exposure values (real and controller) are inversely proportional to the outside temperature, with peak exposure occurring at the lowest temperature (around 0°C). The controller functions as intended, to shift almost all house ventilation to warmer periods of the day and year (in heating season).

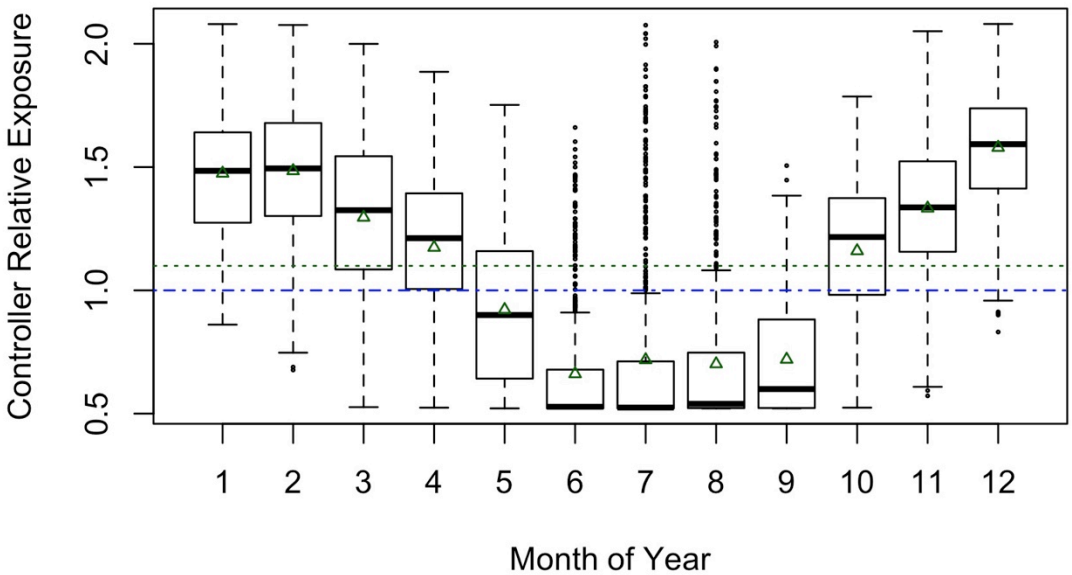


Figure 63 Monthly boxplot distributions of controller exposure for the VarRe TSVC in a 1-story 1 ACH_{50} home in CZ16 (Blue Canyon). Peak exposure targets of 2.1.

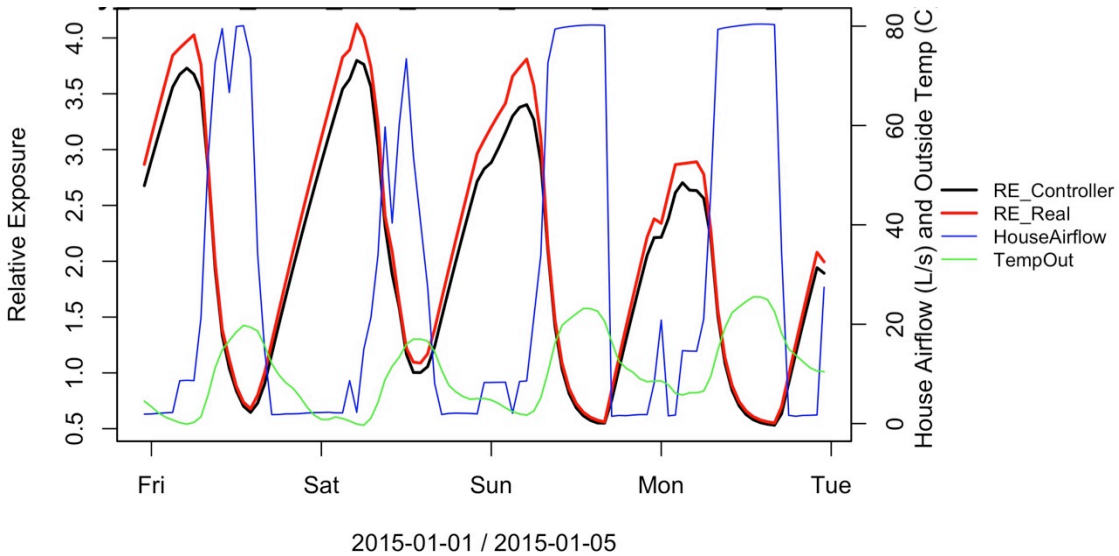


Figure 64 Time-series illustration of the VarRe TSVC controller in a 1-story 1 ACH_{50} home CZ10 (Riverside), with a fan size multiplier of 2 and a peak heating exposure target of 4.1. Includes real and controller exposure, along with whole house airflow and outside temperature.

5.4 Occupancy Controls

For each case (combination of prototype, envelope leakage and climate) we show the Occupancy controller percent ventilation energy savings for site energy (Figure 65) and TDV (Figure 66) using the raw simulation outputs. We then show the same results when normalized by relative exposure for site energy (Figure 67) and TDV (Figure 68). All cases assume the standard OSVC control (ventilation off while unoccupied), with 1st shift, 9-hour daytime absences on weekdays.

Overall, the savings from OSVC were much lower than those achieved using TSVC approaches. This is not surprising, given that the energy associated with ventilation is entirely dependent on the temperature difference between the house and outside. A temperature-aware controller should perform better. 1st shift occupancy controllers effectively behave opposite of our temperature controllers—they reduce ventilation during the mildest times of day (mid-day) and increase ventilation during the more extreme periods (evening/night). These effects are coupled with the fact that our OSVC accounts for pollutant emissions during the unoccupied period, which means that a high ventilation rate recovery period is needed at the start of occupancy. The net-effect is that total ventilation airflow is not reduced very much (overall median of 2.4% reduction in whole house airflow). Past DCV approaches did not account for unoccupied emissions and therefore dramatically over-predicted how much ventilation rates could be reduced while maintaining equivalent exposure. The limited energy savings predicted here align well with those made across U.S. climates by Less & Walker (2017), where Occupancy control savings were substantial only in the most cooling-dominated locations (e.g., Miami, FL).

While the OSVC is very consistently able to deliver annual integrated occupied exposure below one, it saves little energy, with some exceptions (most notably the 2-story 5 ACH_{50} case in CZ 16 with nearly 50% savings). In fact, the controller is just as likely to increase ventilation energy, as it is to save energy. This occurs because in many cases, the OSVC fails to reduce ventilation rates, while it succeeds at shifting ventilation over the hours of the day in a way that increases the net-ventilation load on the HVAC. During heating season, the OSVC reduces ventilation during the mildest, most beneficial times of day (roughly from 9-5pm). During the cooling season, the OSVC does reduce ventilation during hot times of day, but it also massively increases the ventilation rate as soon as occupants return home (at 5pm), which is still a very hot time of day; in fact, it is the peak time of day for cooling load and grid stress.

Normalized percent site savings improved marginally, with a clear pattern across all climate zones of increasing savings with more envelope leakage and in 2-story homes. In nearly all cases, the use of the AIM-2 infiltration model improved normalized performance relative to the Qinf approach. TDV savings remained erratic even when normalized, with greater TDV savings in leakier, 2-story homes, and some notable cases with increased normalized TDV energy use (such as the airtight 1-story cases in CZ3, 10 and 16).

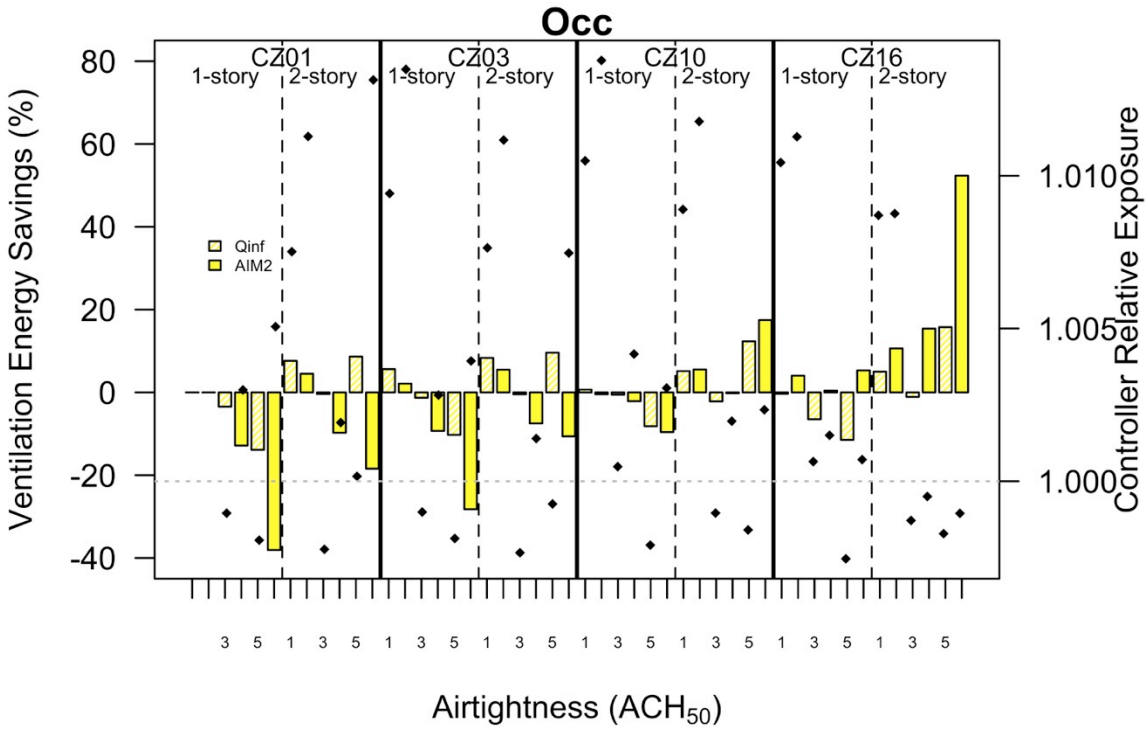


Figure 65 Occupancy SVC ventilation energy savings.

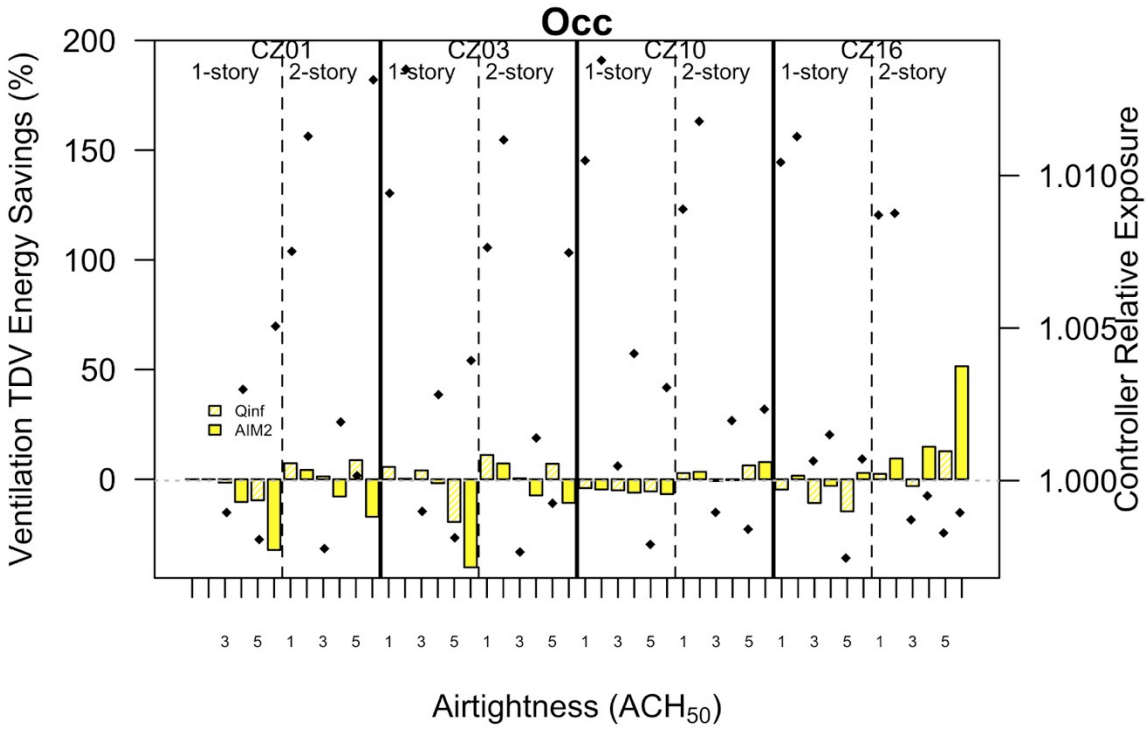


Figure 66 Occupancy SVC ventilation TDV energy savings.

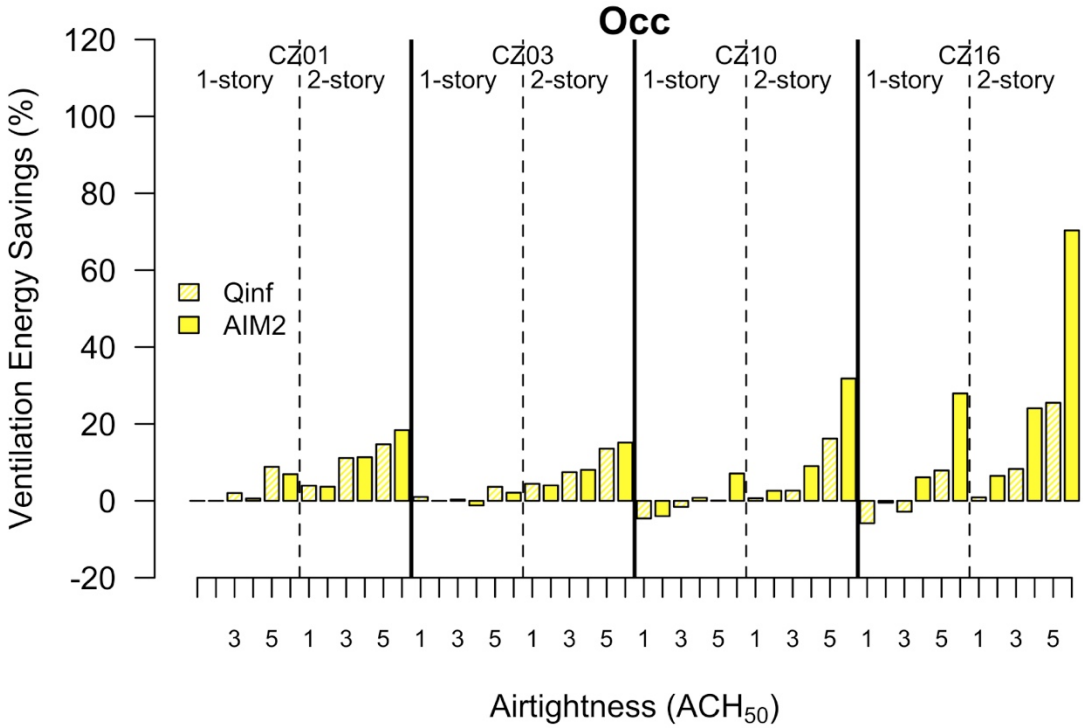


Figure 67 Occupancy SVC normalized ventilation energy savings.

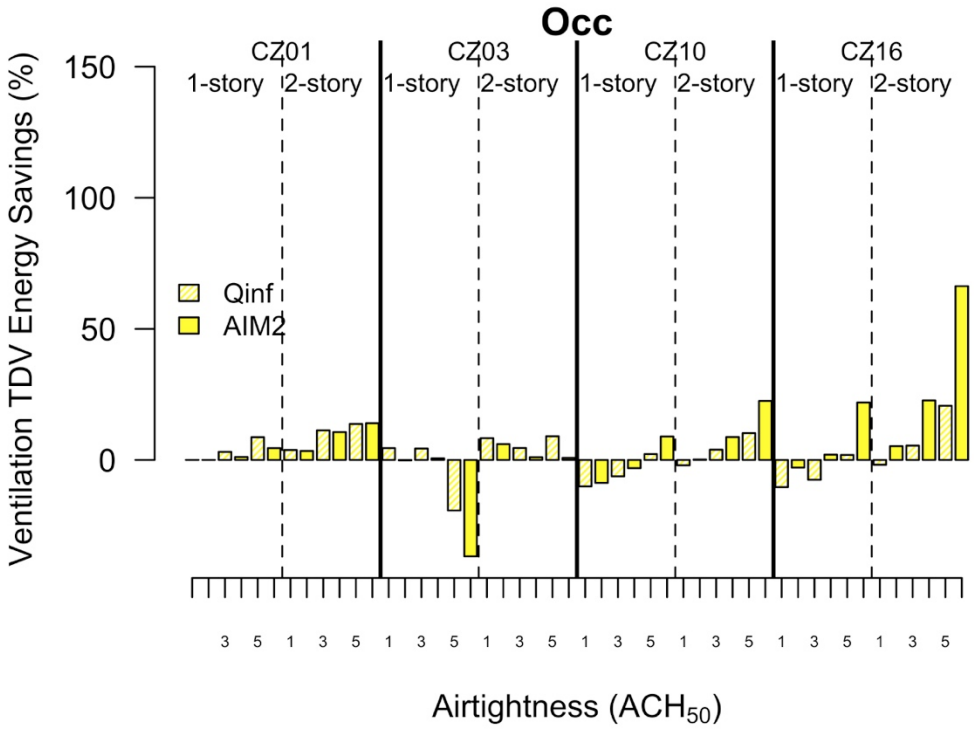


Figure 68 Occupancy SVC normalized ventilation TDV energy savings.

An illustration of the Unocc SVC is provided in Figure 9. The day begins with the IAQ fan maintaining relative exposure (*relExp*, red line) near 1. Light grey highlighted periods show IAQ fan on periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home, and it is reduced back below one during the recovery period. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

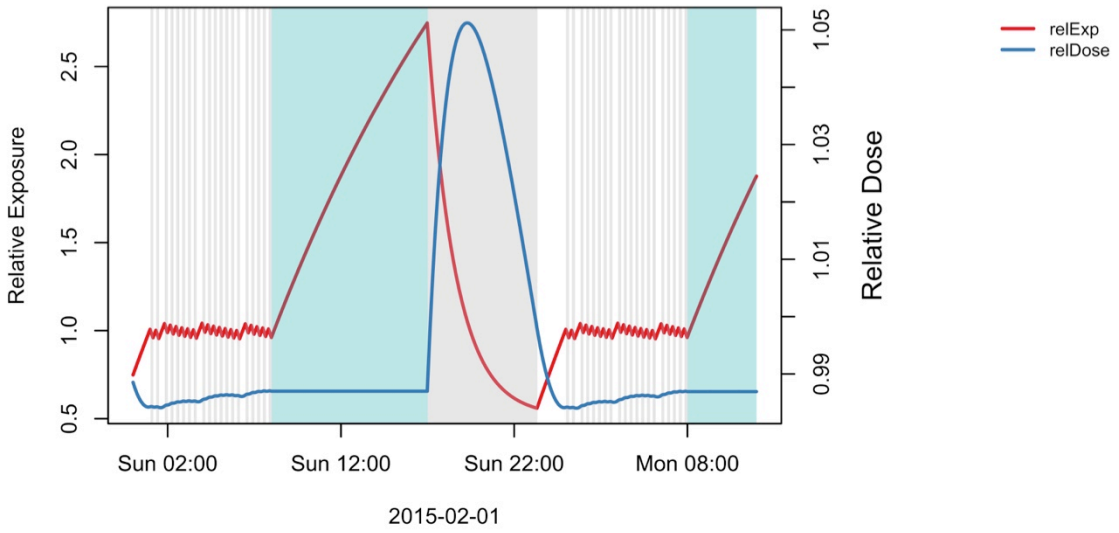


Figure 69 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

5.4.1 Variations on the Occupancy Controller

As described in Section 3.2, we tested three variations on the Occupancy SVC. First, is the standard control, where the fan is turned off during unoccupied periods, and the controller then increases ventilation during occupancy to ensure daily integrated occupied exposure is below one. Second, we tested a 1-hour pre-occupancy flush out where the ventilation system operates at full airflow during the hour prior to occupancy, and then the controller takes over and controls daily integrated occupied exposure below one. Finally, we tested a controller where the IAQ fan is turned to 35% of the 62.2-2016 baseline fan airflow during unoccupied periods, and then the controller ensures daily-integrated occupied exposure less than one. The median ventilation site energy savings for each of these variations is summarized by climate zone in Figure 70 (see Figure 71 for TDV ventilation savings). We show only raw, non-normalized savings to illustrate these variations in the occupancy controller.

Overall, the 1-hour flush out pre-occupancy provides the highest ventilation energy savings (CZ16 exception), though median savings are still very low, with median values of 3-10% depending on climate zone. TDV ventilation savings are similar, with the 1-hour flush out still performing the best. The 1-hour flush saves the most energy because it allows the largest reduction in total ventilation airflow relative to the baseline continuous fan. The median reduction in whole house airflow was 3.7% for the 1-hour flush cases, while only 0.9 and 1.11% for the standard OSVC and the 35% OSVC. The daily airflow requirements for an equivalent control decrease as the peak exposure goes down, and the 1-hour flush out cases had median peak exposure of 1.7, compared with 2.4 and 1.8 for the standard OSVC and the 35% OSVC. The 35% unoccupied airflow strategy does reduce peak exposure similarly to the flush

out, but it fails to reduce overall ventilation rates, because the airflow is higher during unoccupied periods. The flush out is a much more efficient (in terms of airflow) way to reduce peak exposure.

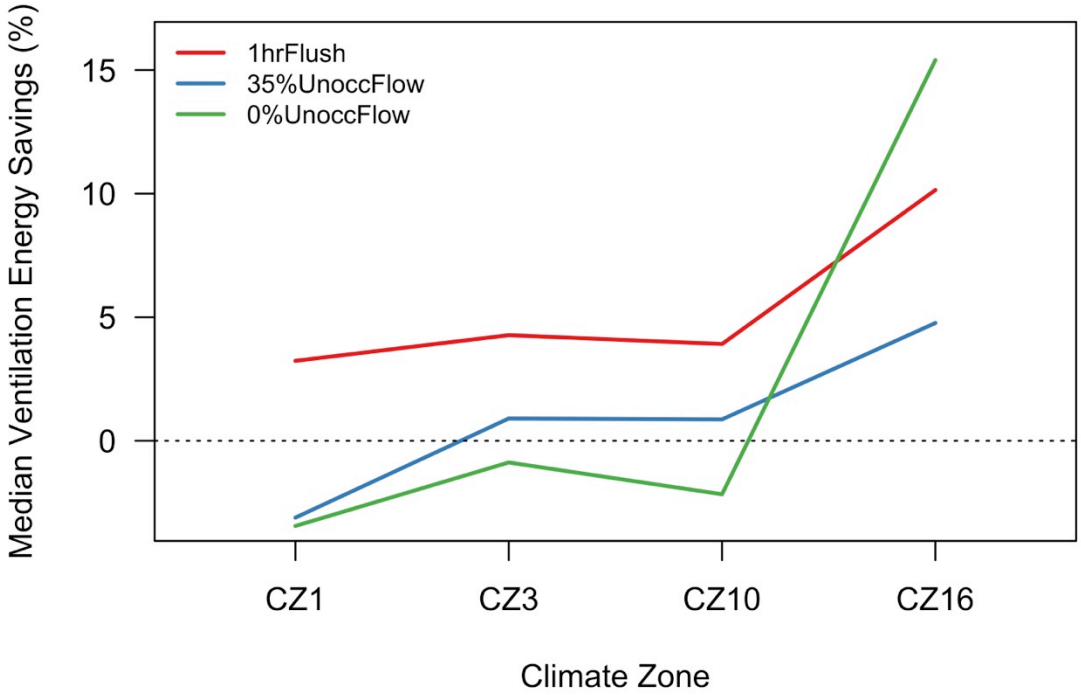


Figure 70 Median ventilation site energy savings for the Occupancy SVC control with no flush pre-occupancy, a 1-hour flush and with low unoccupied ventilation airflow.

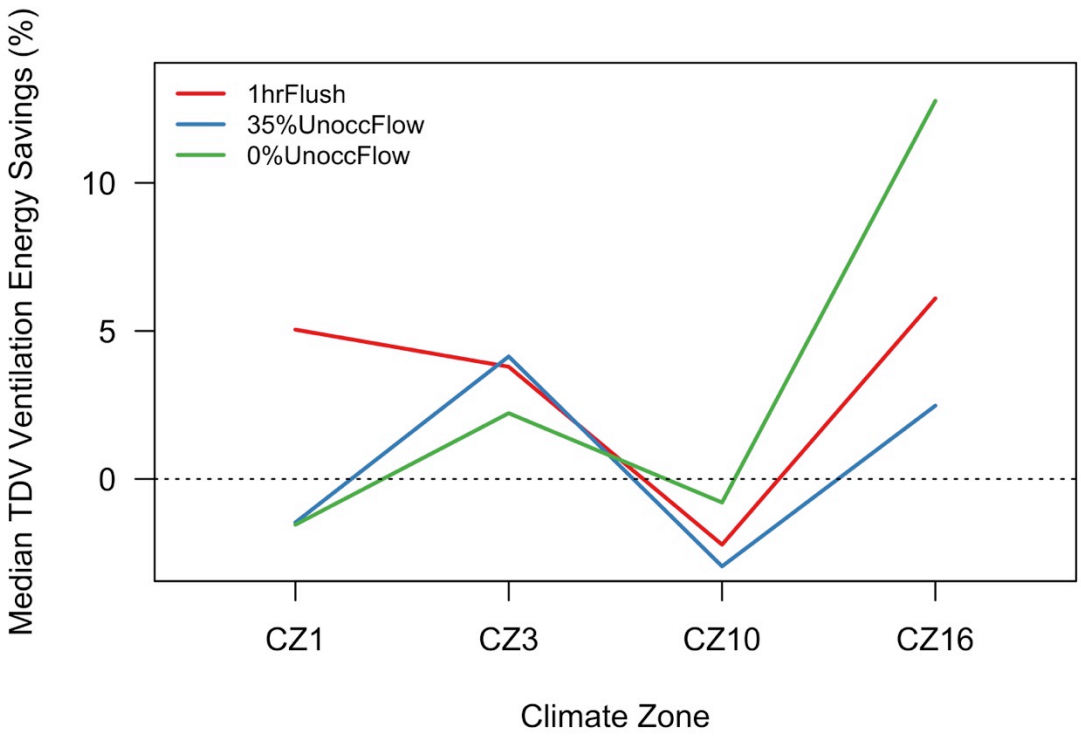


Figure 71 Median ventilation TDV energy savings for the Occupancy SVC control with no flush pre-occupancy, a 1-hour flush and with low unoccupied ventilation airflow.

5.5 Addition of Auxiliary Fan Sensing to TSVC and OSVC

All temperature and occupancy controls were tested with an auxiliary fan sensing capability, which built upon the original controls to simply account for other exhaust airflows in the controller's air exchange estimates. This allows the controllers to operate the main IAQ fan less (or at lower airflow), because it is aware of other concurrent airflows. For example, if the VarQ controller calculates that the IAQ fan must operate at full capacity, but the clothes dryer is operating, the controller then reduces the IAQ fan flow accordingly. We show only non-normalized results for the auxiliary fan add-on controls.

The overall median ventilation site energy savings for compliant cases are shown for each control type in Figure 72, with and without auxiliary fan sensing (TDV savings are shown in Figure 73). Here we see roughly a 10% average boost in ventilation savings when adding auxiliary fan sensing to the existing controls. For individual cases, the incremental benefit of auxiliary fan sensing decreases as the overall savings increase. For the best-performing cases, adding the auxiliary fan sensing adds a small 3-5% additional benefit. For the worst performing cases, auxiliary fan sensing could add 14% savings. Auxiliary fan sensing provided greater TDV benefits, because it largely allowed reduced ventilation rates during peak hours when occupants returned home and used auxiliary ventilation devices for cooking and bathing. The VarQ controller had little incremental TDV energy benefit from

auxiliary fan sensing, because aggressive reductions in ventilation airflows during peak demand periods were inherent in its control schema.

There is some variability by control type, but that is not due to fundaments of the controls and how they interact with auxiliary fan sensing. Rather, these groupings include different homes, because sometimes the inclusion of auxiliary fan sensing changed the compliance status of the case (annual exposure below one). In fact, with the exception of the Lockout control, inclusion of auxiliary fan sensing always increased the fractions of control cases that were compliant with the exposure below one requirement. These different groupings shift the medians up and down. For example, it looks like the VarRe gets much more benefit from auxiliary fan sensing than do the VarQ cases, which results from including different cases in the median estimate.

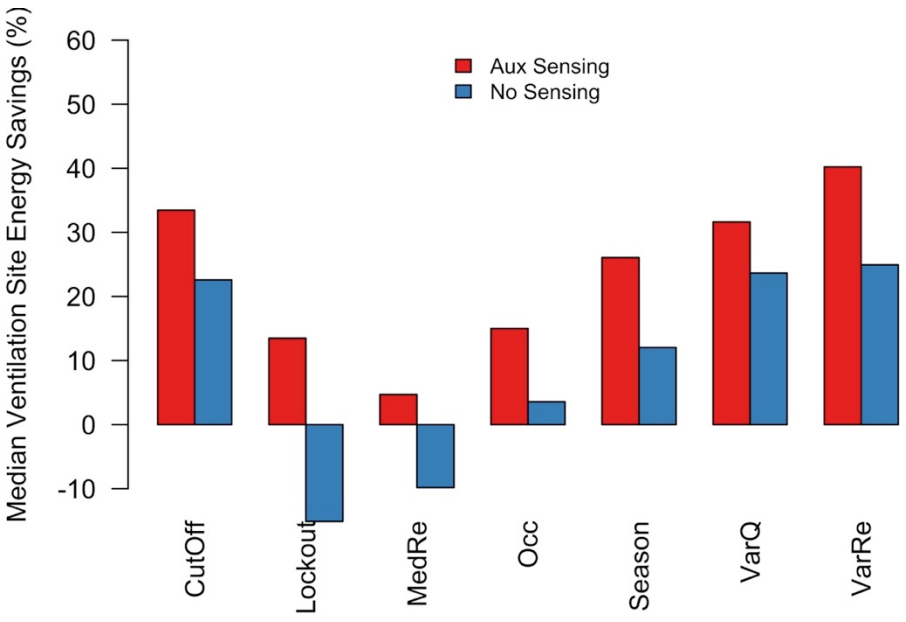


Figure 72 Median ventilation site energy savings for compliant SVC with and without auxiliary fan sensing.

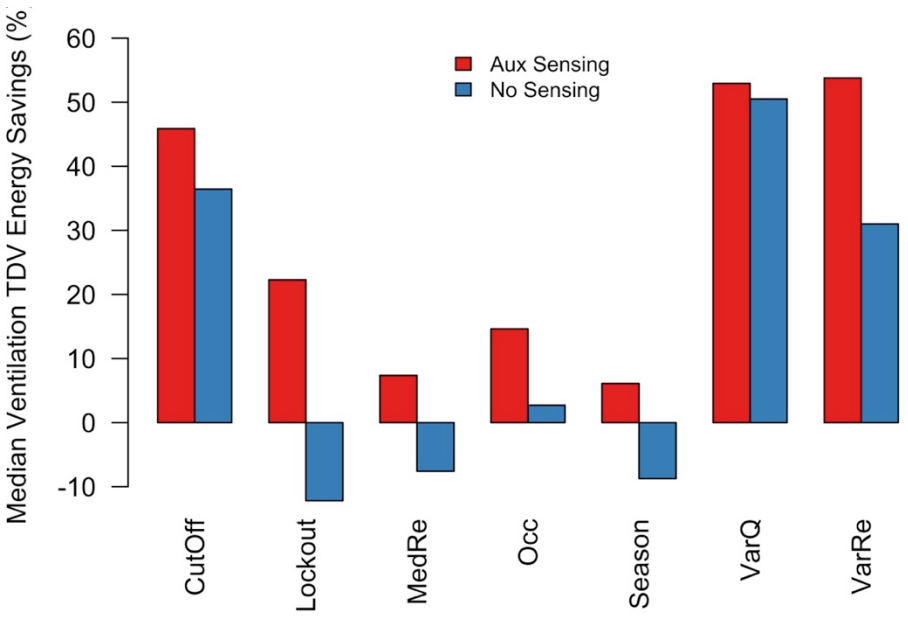


Figure 73 Median ventilation TDV energy savings for compliant SVC with and without auxiliary fan sensing.

We noted above that auxiliary fan sensing reduced controller exposure, but what is more notable is how it increased real exposure. We show these changes in Figure 74. On average, controller exposure is reduced by about 1%, or less, when using auxiliary fan sensing, which makes more cases/controls compliant. These small changes occur because of the non-linearities when combining unbalanced mechanical ventilation with infiltration (the calculations for fan sizing do not exactly match the calculations for recombining mechanical flows and infiltration) and issues such as timing of when auxiliary fans are operating and the ventilation fan is being turned on and off by the various control strategies. But this feature also consistently increases the real exposure, by 7% on average. Fully 75% of the control cases still had real exposure below one (though they were higher than without auxiliary fan sensing), and real exposure was at most 1.1. So, auxiliary fan sensing does contribute to meaningful energy savings of roughly 5-15%, but it does so by reducing the overall air exchange rate and increasing occupant exposure to contaminants. This is allowed by the ASHRAE 62.2-2016 ventilation standard, but may not be advisable.

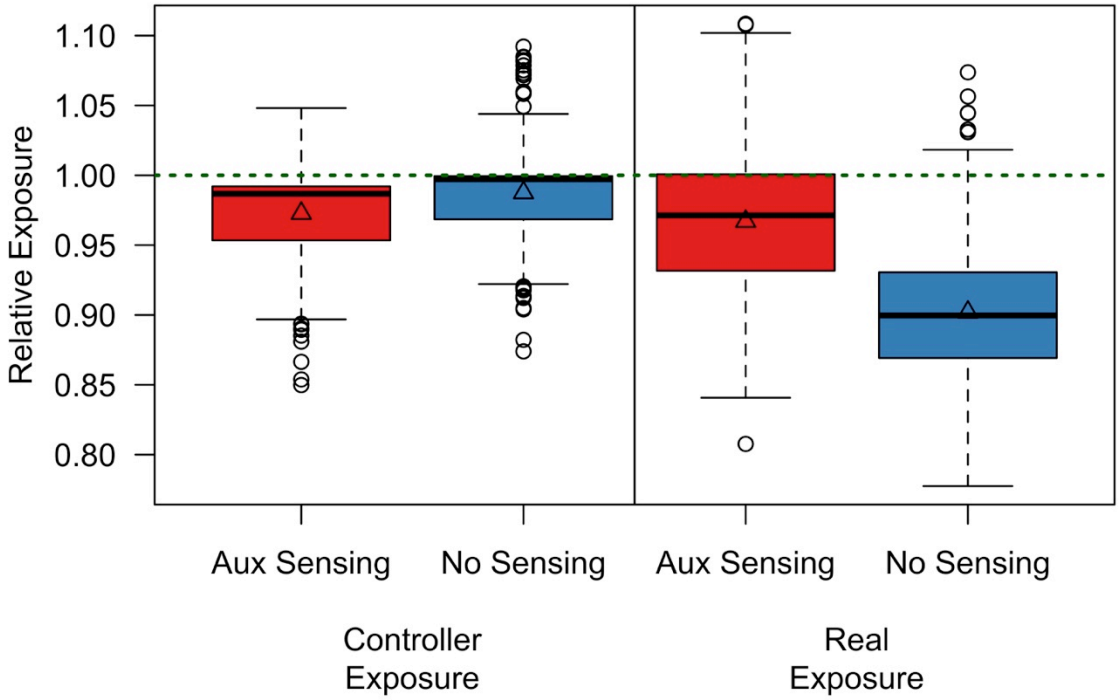


Figure 74 Controller and real relative exposure, compared by auxiliary fan sensing status.

6 Discussion

This discussion focuses on the impacts that the smart controllers had on relative exposure, IAQ and house ventilation rates. We begin by describing the margins of failure for non-62.2 compliant cases where relative exposure was >1.0 (Section 6.1). Next we describe the impacts of smart controls on: reductions in exposure (Section 6.2), increases in peak exposure (Section 6.3) and changes to exposure during occupied and unoccupied hours of the year (Section 6.4). We describe the daily vs. seasonal shifting of exposure for different control types (Section 6.5). House airflow is discussed in terms of increases in ventilation rates with SVC (Section 6.6) and comparisons of the energy impacts of SVC with those of envelope air sealing (Section 6.7). Finally, we discuss next steps for inclusion of smart ventilation controls within the realm of demonstrating Title 24 energy code compliance (Section 6.8). A further discussion of simulation parameter sensitivity is summarized in Appendix S.

6.1 Failure Margins for Non-Compliant Controls

A substantial minority of smart control cases failed to meet the requirement of ASHRAE 62.2-2016 that annual average relative exposure be less than or equal to one. While these failures are unfortunate and show the potential inconsistent exposure in controls that shift ventilation seasonally, it is important to note the

margins by which the control exposure exceeded 1.0. We show the distributions of failure margins aggregated by control type in Figure 75. When most controllers failed, they failed by relatively small average margins of 0 to 3% (i.e., 1-1.03 exposure). These controllers did not satisfy the ventilation standard, but they did have annual exposures commensurate with those achieved by continuous baseline ventilation fans sized to ASHRAE 62.2-2016 (see the Base_Fan cases in Figure 75).

We struggled in this project with how to determine if a control case was equivalent to the continuous fan. We ultimately have deemed all cases with controller exposure above 1.0 by any margin whatsoever to have failed. This is in accordance with the requirement in the ASHRAE standard.

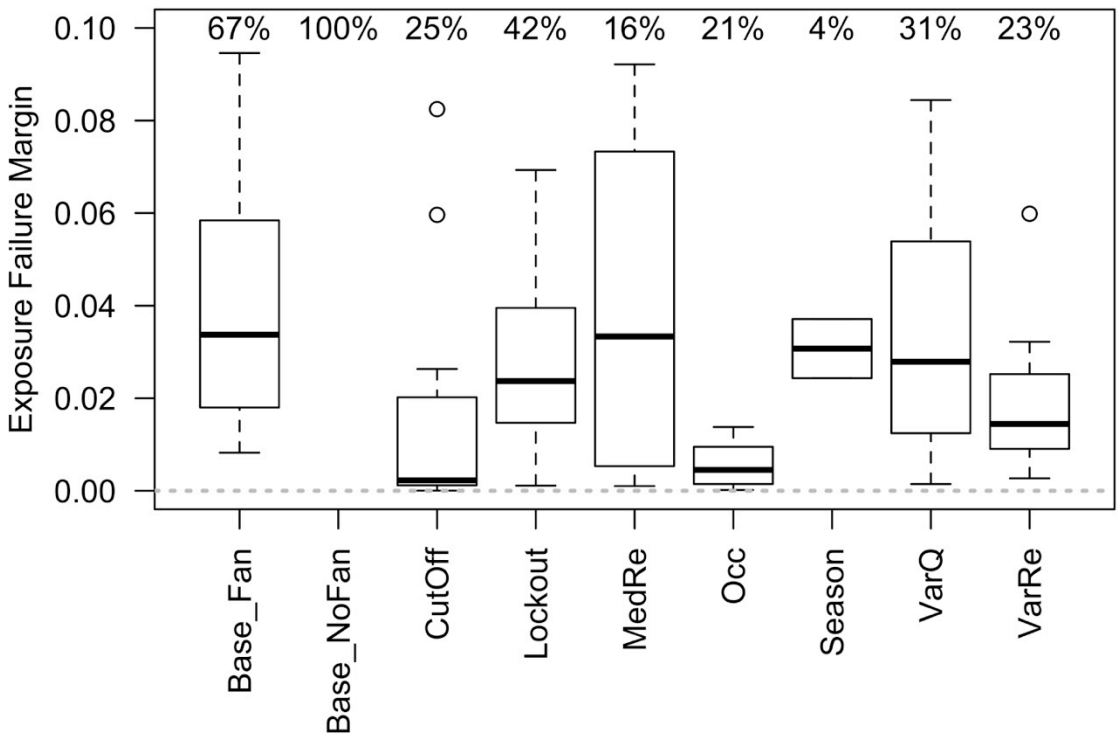


Figure 75 Margin of failure for simulations failing to meet equivalence requirement of controller relative exposure <= 1.0. Fraction of cases that failed indicated in text at the top.

6.2 Reductions in Exposure

Overall, the SVC reduced the real and controller relative exposure when compared with the continuous fan baseline simulations, which translates to improved IAQ for the smart control cases. The distributions of reductions in controller and real relative exposure are shown by boxplots in Figure 76 and Figure 79. Across the board, smart controls reduced real relative exposure by between 0 and 20% (averaging between 5 and 10%), while reductions in controller exposure were somewhat smaller, ranging from 0 to 15% reductions relative to the continuous fan baselines (averaging between 3 and 5%). We also illustrated these reductions in the plots of the best-performing controllers for each home (see Figure 18). The top-

performing controllers, in addition to reducing ventilation energy, also improved IAQ by reducing pollutant exposure between roughly 0 and 15%.

Smart controls reduced real and controller relative exposure for two main reasons. First, most baseline continuous fan cases had exposures between 1 and 1.09, which means they were under-ventilated relative to the 62.2-2016 whole house target airflows. This bias in 62.2 fan sizing is discussed in Appendix R. Second, the smart controls were designed to achieve controller exposures below one, which meant a design target in most controllers of 0.97 to account for imperfections in controller design and operation. As a result, many controllers inadvertently had annual exposures well below 0.97, reducing the exposure even further relative to the baseline fan cases.

This systematic bias towards high exposure in the reference baseline cases and low exposure in the control cases was the critical factor that led us to normalize the energy savings results and to present them in parallel with raw simulation results in Section 5.

We recommend that future assessments of smart ventilation controls designed to comply with ASHRAE 62.2-2016 follow a similar normalization method to ensure apples-to-apples IAQ and energy comparisons. This should be done for both baseline and smart control cases. Furthermore, we suggest that the ASHRAE standards committee responsible for 62.2 should change the superposition models embedded in the standard, so that they are a forwards-backwards identity. This would ensure that one arrives at the same value, whether sizing a fan (Qfan) using a target whole house flow (Qtotal) and infiltration estimate (Qinf), or using the resulting fan flow and infiltration estimate to calculate whole house flow for use in exposure calculations. Hurel et al (2016) provide all superposition models as identities, including those currently in 62.2. The equations would become marginally more complex when estimating whole house flow for use in exposure calculations. This would eliminate the systematic bias towards high exposure in baseline cases, but it would not necessarily impact the varying exposures achieved by a smart controller.

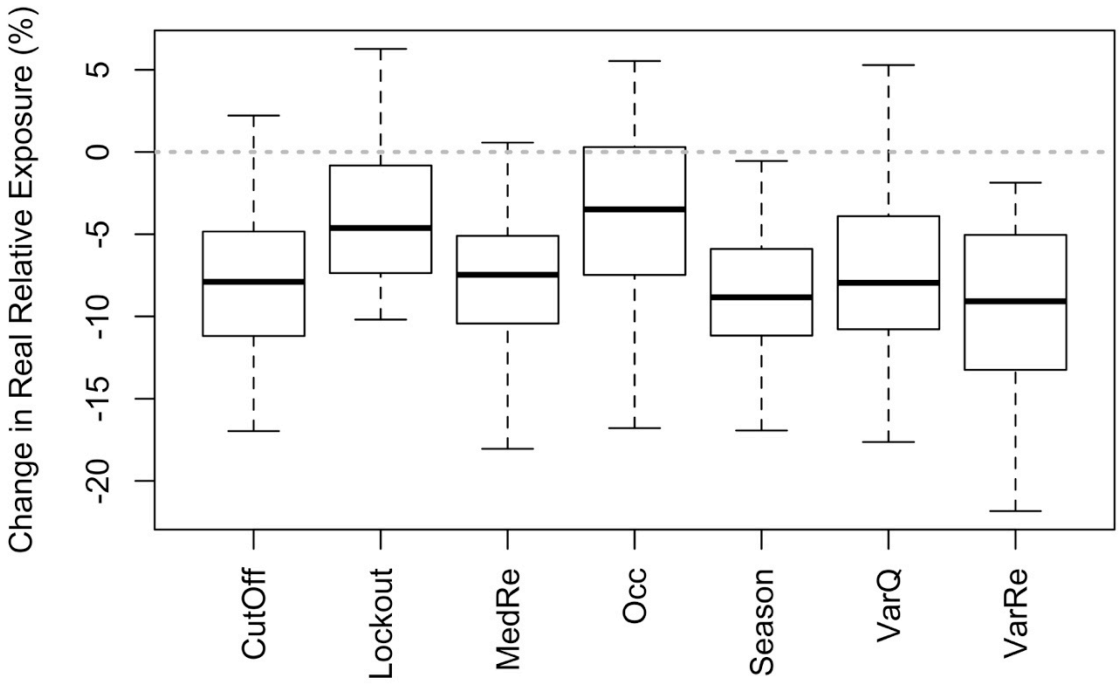


Figure 76 Reduction in real relative exposure, by smart control type.

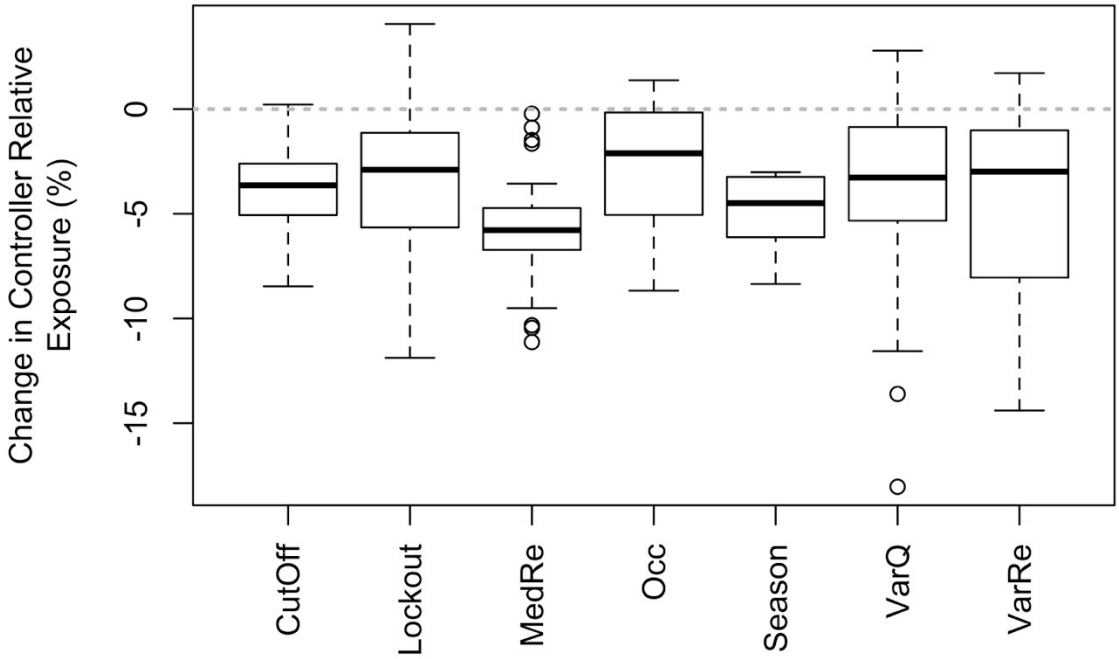


Figure 77 Reduction in controller relative exposure, by smart control type.

Consistent with this, we also compare the controller exposure and the real exposure for every simulated case in Figure 78, along with the unity line dashed in grey. We note that for nearly all simulated cases, the real exposure is less than the exposure predicted by the ventilation controller, which makes all of our estimates essentially conservative in terms of IAQ impact. This is due to other airflows not accounted for by the controller, which the real exposure includes (e.g., local exhaust devices, and in Qinf cases, time-varying infiltration).

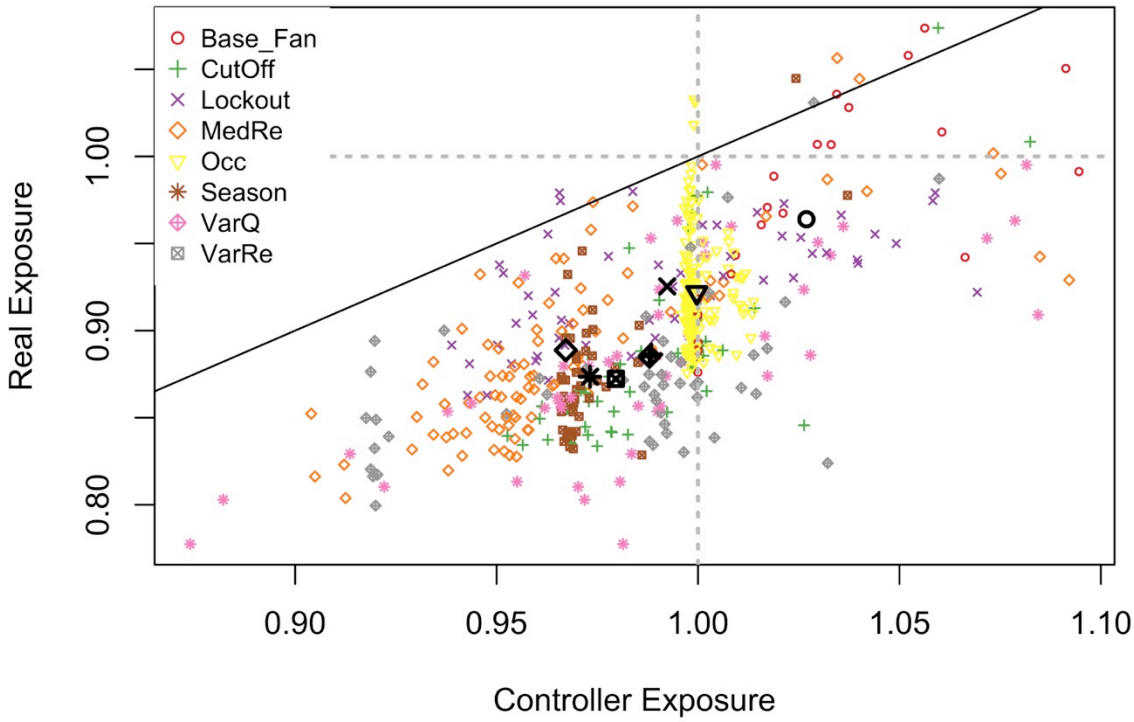


Figure 78 Controller vs. real relative exposure.

6.3 Increased Peak Exposure

While most smart controls saved energy and improved IAQ, they also increased peak exposure to the occupants, resulting from reduced air exchange rates when hot or cold outside. The peak annual one-hour relative exposure values are shown for each control type in Figure 79. For reference, the ASHRAE 62.2-2016 ventilation standard allows a peak exposure of 5 when demonstrating compliance through Appendix C. The big outlier in Figure 79 is the VarQ smart controller, which has much higher peak exposures than its counterparts, with a peak exposure in one case that exceeded the limit of 5 (note that this is because, unlike a real-time controller, this control strategy does not perform exposure calculations and, therefore, cannot limit peak exposure). The nearest counterpart for the VarQ is the VarRe controller. They work on similar principles, with a similar control structure, yet the peak exposures are much lower in the VarRe controller, averaging below 2 and at most 3.5. The reason VarQ experiences high exposure excursions is that the controller will actually just turn the ventilation fan off if it is cold or warm enough outside. In

contrast, the VarRe controller simply targets an increased exposure level (lower ventilation rate) during those same periods. The VarQ controller could easily be adjusted to target a low airflow rather than 0 at extreme conditions, which would eliminate this issue. The Cutoff controller is also worth noting, because it was one of the top energy performers, and its peak exposures are very low—averaging below 1.5 and always below 2. The Cutoff control was actually optimized by targeting a low peak exposure, but doing so for as many hours of the year as possible (as opposed to a high exposure target for fewer hours). Overall, we expect peak exposures in these situations to worsen with increasing airtightness and in more mild climates. But some controls are good at limiting these peaks (VarRe and Cutoff), and others are not (VarQ).

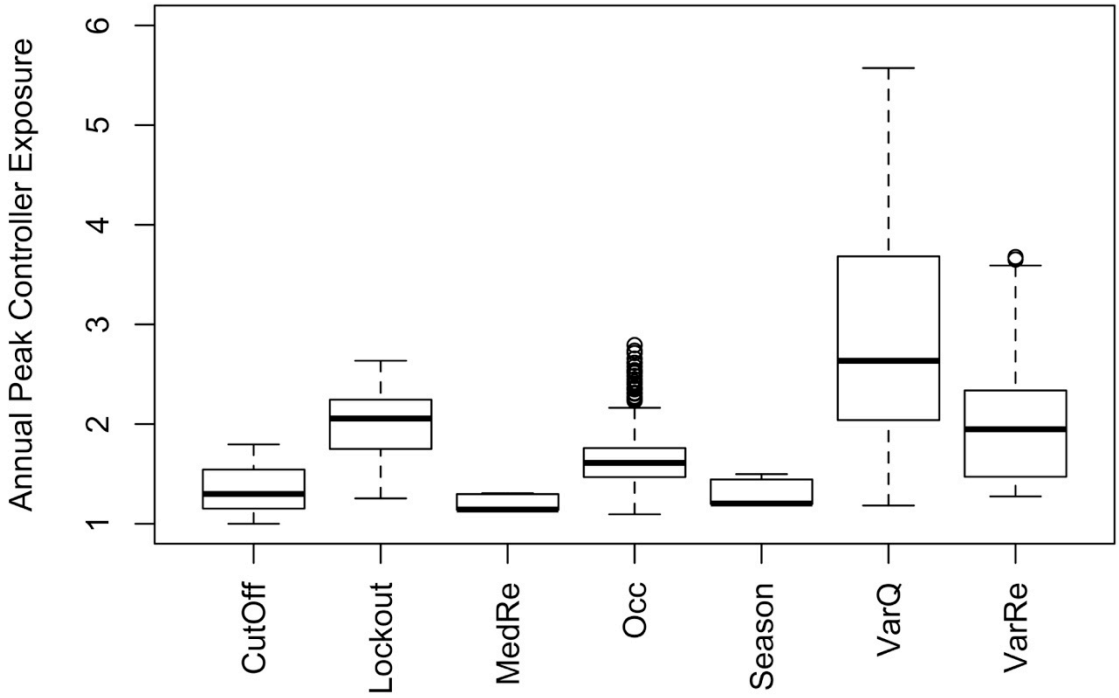


Figure 79 Annual peak one-hour controller relative exposure.

6.4 Occupied vs. Unoccupied Exposure

We have noted elsewhere that the Occupancy and Temperature SVC behave in different ways, with the temperature-based controls generally reducing ventilation during the coldest/hottest periods and increasing it at other times. Over the course of a day in the heating season, we expect our TSVC to increase ventilation during the warm, daytime hours when the home is unoccupied. The same controllers then reduce the ventilation rate during colder nighttime hours when occupants are present. We expected that this approach might bias the TSVC towards a net-increase in occupant exposure, because the controls (and the ASHRAE 62.2-2016 standard) weight exposure equally during occupied and unoccupied hours.

To assess this, we applied a standard occupancy schedule to our TSVC results, using the same 9-hour, 1st shift absence as in the Occupancy SVC cases. We then averaged the time-series controller and real exposure values for all occupied and unoccupied hours to assess this potential bias. For each control type, we calculated the median occupied and unoccupied control exposure across all cases, and these overall values are shown in Figure 80. Clearly, the occupied and unoccupied hours had quite similar controller exposure values across all control types, except for the Occupancy SVC, which purposefully maintains high exposure during unoccupied periods. In fact, for most of the TSVC, occupied exposure was slightly less than unoccupied exposure (except VarRe). In any case, the values are essentially indistinguishable over the course of the year. This pattern is the same when assessing real exposure by occupancy status. These results may reflect a balancing of TSVC behavior over the course of heating and cooling seasons. During cooling season, we expect increased ventilation during occupied, nighttime hours and reduced airflow during the hot, unoccupied daytime hours. This might balance out the expected biased pattern in the heating season. Finally, it is worth noting that all TSVC actually achieved lower occupied exposure on average than the Occupancy SVC did. We strongly conclude that the TSVC pose no risk of biasing occupant exposure high, even though the controls are unaware of the occupancy status.

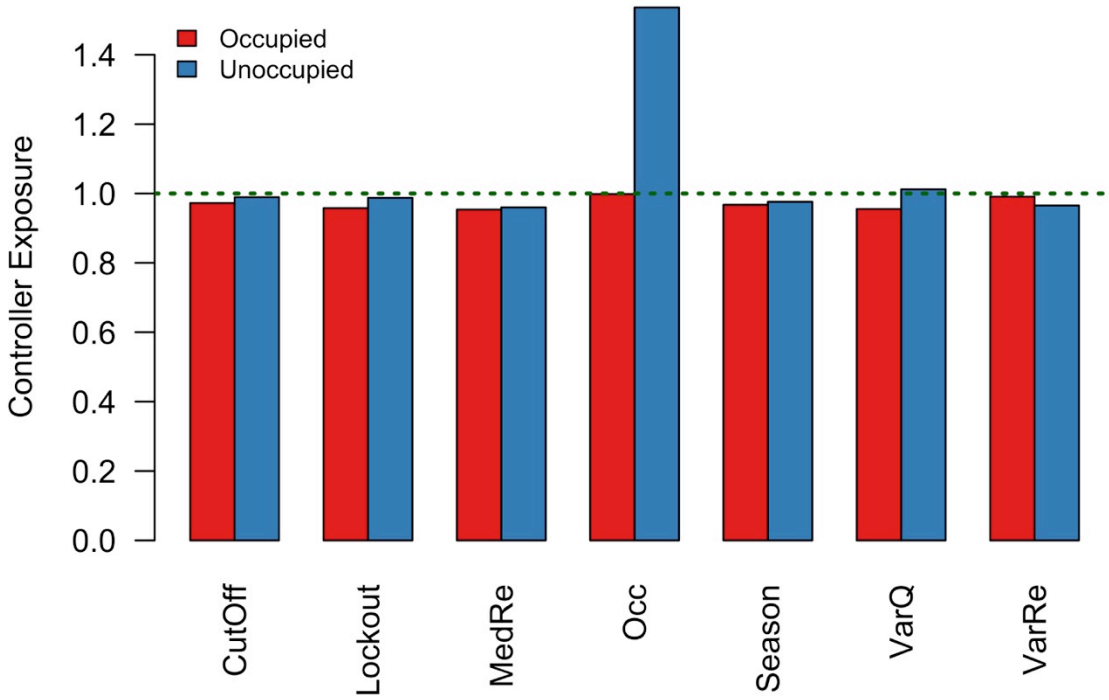


Figure 80 Comparing controller exposure by occupancy status for all smart controls (medians calculated within each control group).

6.5 Daily vs. Seasonal Controllers

The smart controls developed and tested in this work differed in the time horizons over which they maintained equivalent exposure with 62.2-2016.

The worst energy performance was for the two control types that targeted equivalent exposure on a daily basis—the Lockout and the Occupancy controls. In these controls, the mean occupied exposure was required to be less than or equal to 1.0 each day of the year. This ensured that the yearly exposure would also be less than 1.0. This approach allowed shifting of airflows only across hours of the day, which limited their effectiveness.

The next-worst performing control was the Running Median (MedRe) controller, which used a 30-day time period for ensuring equivalent exposure. This controller was intended to ensure that each month's mean occupied exposure was less than or equal to 1.0, which again ensured annual exposure was also below 1.0. The MedRe was able to shift ventilation airflows between days and weeks of the month, but not between months/seasons. This additional flexibility gave it a marginal advantage over the daily Lockout and Occupancy controls.

Finally, the controls with the greatest energy savings were those that targeted equivalent exposure on an annual basis—Seasonal, CutOff, VarQ and VarRe. These controls were able to shift ventilation airflows across months and seasons of the year, and whether by-design or through optimization, they all reduced ventilation airflows during the heating season and increased them during the cooling season. The Seasonal control was the simplest approach that did this seasonal shifting, and it did nothing other than reduce ventilation in winter and increase it in summer. This worked well in many contexts, but it had predictable TDV energy penalties, due to the emphasis on peak period electricity consumption in TDV assessments. But by far the best-performing strategies—CutOff, VarQ and VarRe—built upon this seasonal shifting of ventilation flows by also varying airflow within each season to take advantage of mild periods and to avoid ventilating during especially hot or cold times.

While the energy benefits were clear, there are also notable downsides to these seasonal-shifting control strategies.

First, it is simply very challenging to design and optimize an annual controller that will achieve exposures below one. Despite careful design and optimization to select control parameters, the simulated controller exposures were often substantially different than the simplified estimates used in the design-phase. For example, the VarRe controller sets an exposure target for every time-step of the simulation based on the season and outside temperature, and it then identifies the maximum RE target such that annually the target exposure values will average to 0.97. The problem is that any given target exposure value cannot necessarily be met at the time-step it is calculated, because when the target moves rapidly (as it does with diurnal temperature patterns), it takes time for the controller to adjust the exposure

(up or down) to the reach the target value in the actual home. It is this lag in the changing exposure values relative to the targets established by the controller that makes these control types unstable and difficult to predict precisely.

Second, some are concerned that the seasonal-type controls maintain seasonal average contaminant levels well above those in the reference condition. These high levels are then offset by low concentrations during other seasons. While consistent with the annual requirements of ASHRAE 62.2-2016, the potential implications of this seasonal shifting are still unknown. For example, we simply do not know if the health and perceived IEQ are actually the same between a case with indoor formaldehyde held constant at 20 ppb, versus varying seasonal levels of 10 and 30 ppb (for 50% of the year, each). Any health detriments between 20 and 30 ppb may very well not be offset equally by health benefits from maintaining 10 ppb during the other season. This may be especially the case for indoor contaminants, such as irritants, odors or moisture.

Yet, this seasonal variability in indoor contaminant levels (and ventilation rates) already happens in actual homes due to a variety of effects, whether intended or not. First, many indoor VOCs are emitted at higher rates with increasing indoor temperatures. So, the cooling season will commonly see higher chemical emissions and measured concentrations. At the same time, many homes operate windows manually to provide ventilation during the cooling season, leading to higher average ventilation rates during these times. Furthermore, all homes experience time-varying infiltration rates, which in real homes will drive time-varying concentrations; again generally lower in particularly hot or cold periods. If anything, the seasonal smart controllers tested in this work will increase ventilation rates when chemical emissions are at their highest (during cooling season), potentially providing further value that is not reflected in our calculations based on a generic, continuously emitted contaminant. All homes experience time-variability in indoor contaminant levels, many seasonally. Our SVC simply exhibit this behavior purposefully.

6.6 Changes in Air Exchange Rate

Except for the Occupancy SVC, all smart ventilation controls increased the annual average air exchange rate of the home, which they must do in order to both dynamically vary the ventilation rate and maintain equivalent exposure (Nazaroff, 2009). Successful smart controllers increased whole house air exchange rates by anywhere from 0 to roughly 40%, averaging around 20% for the most successful controls. This counterintuitive result is possible, because the controllers shift airflow based on temperature, and the increased flows occur when weather is mild, with reduced energy impact. We show the distribution of increases in annual mean air exchange rate for each control type in in Figure 81. Notice how the occupancy controller saves energy by reducing the average ventilation rate relative to the baseline case. Some occupancy control cases increased the ventilation rate relative

to the baseline cases, because the baselines have mean relative exposures greater than one, while the control cases are all less than one (i.e., 62.2-2016 compliant).

We have shown that increasing the house ventilation rate can be done while saving large amounts of energy relative to a continuous fan, but there are downsides as well. First, a larger fan is needed, with larger ducting, more potential noise, etc. Second, increasing the ventilation rate by up to 40% increases IAQ fan energy by at least that same fraction, which can substantially eat into ventilation savings, unless the controller is well designed and the fan power is low. Third, in locations with compromised outdoor air quality (i.e., Ozone in the central valley foothills, or $PM_{2.5}$ in downtown Oakland), this has the potential to greatly increase indoor concentrations of outdoor contaminants, mainly particulates and products of combustion (oxides of nitrogen). Finally, in hot-humid climates, increasing the ventilation rate by 20% will almost certainly transport more moisture into the home, leading to potential comfort problems and concerns about mold growth. This will be exacerbated by the overall trend with most of our TSVC to increase the ventilation rate drastically during the summer, while reducing it during the winter. The cooling season has the highest outdoor humidity in hot-humid climates, so this is likely a poor ventilation pattern for moisture control in humid environments.

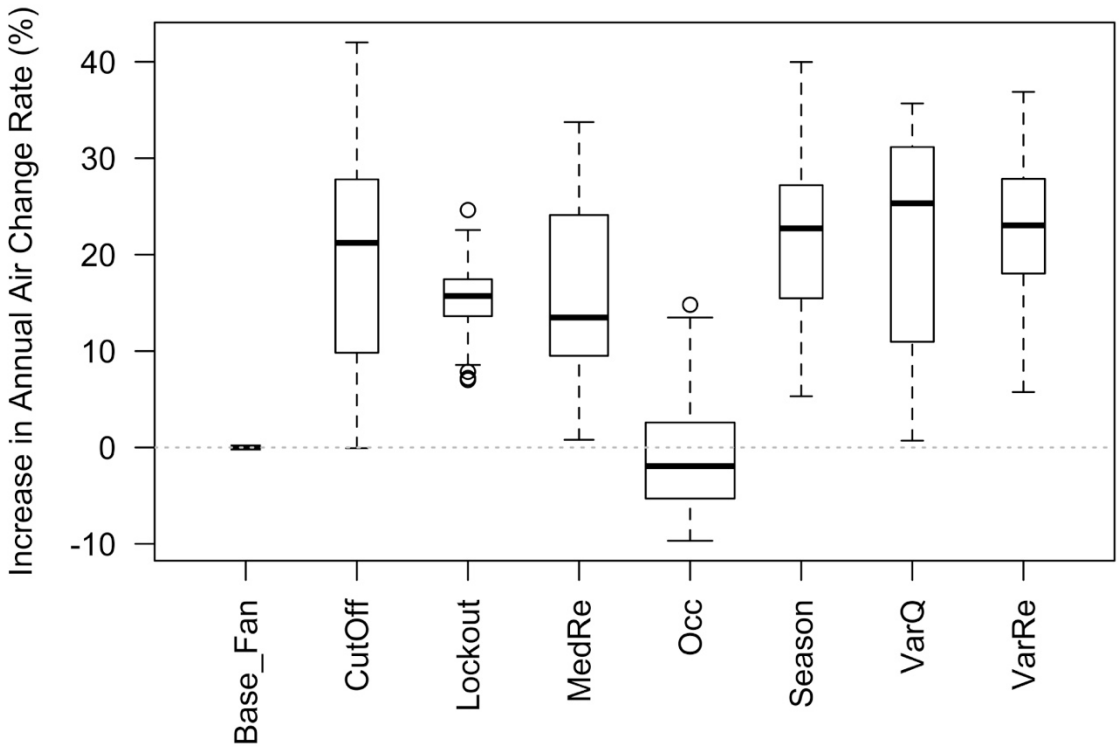


Figure 81 Increase in annual mean air change rate distributions by control type, ALL cases.

6.7 Smart Controls vs. Airtightening

We are also interested in how smart ventilation controls compare with air sealing a home; maybe similar energy performance can be attained by selecting the optimum

airtightness for a given prototype and climate zone, and the added complexity of smart controls are not needed. Overall, our results show that in all but one scenario, a 62.2-compliant smart ventilation control will be a better energy conservation approach than airtighening, assuming that the home is ventilated in compliance with ASHRAE 62.2-2016. Notably, energy savings from air sealing the building envelope are the result of reduced ventilation rates, increased relative exposure and poorer IAQ. In contrast, the SVC save more energy and do so while reducing exposure and improving IAQ relative to the constant fan baseline cases.

In Figure 82 we show the total HVAC raw site energy consumption predicted for the baseline fan and best-performing smart controls at each airtightness level for the 2-story large prototype homes located in CZ10. The bars are colored by control type and are shaded (slanted lines) according to the infiltration accounting method (Qinf vs. AIM-2) with the least energy use for the given controller (see TDV energy in Figure 84). We see that of the baseline continuous fan cases, the 3 ACH_{50} home uses the least site HVAC energy. But there are smart controls at each airtightness level that use less energy than this constant fan minimum case. The VarRe control in a 3 ACH_{50} home with AIM-2 infiltration uses the least HVAC energy of all, followed very closely by the VarQ control in the 1 ACH_{50} home using Qinf infiltration accounting. For this prototype and location, either the Qinf or AIM-2 infiltration assumptions give good performance.

In this study, we used the ASHRAE 62.2-2016 fan sizing method, which increases the required fan airflow as infiltration airflows are reduced with more airtight envelopes. The core idea of this sizing method is that it ensures the same whole house ventilation rates across differing levels of airtightness, climate zones and house types. This method is not perfect, but in general, there is little benefit to air sealing a home in California when ventilating in this manner, because the ventilation rate is designed to be fixed independently of the envelope leakage. Some benefit can be received, because the airtight home with a larger fan will have lower ventilation rates during very hot, cold or windy periods, compared with the leaky home with the smaller fan. This benefit is small in mild California climates. A recent statewide assessment (Chan et al. 2019) of this phenomenon suggests weighted average HVAC energy savings of 1-2% when imposing a 3 ACH_{50} airtightness limit on new CA homes. When fan size is not adjusted by envelope leakage, the savings increase marginally to the range of 3-5% of total HVAC energy use.

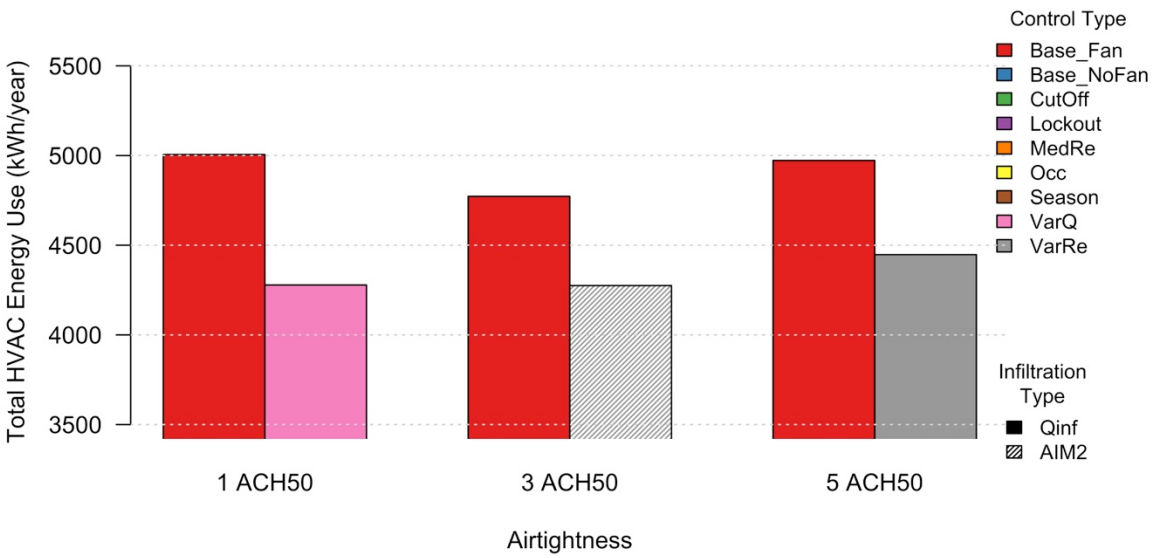


Figure 82 Total HVAC energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 2-story homes in CZ10 (Riverside).

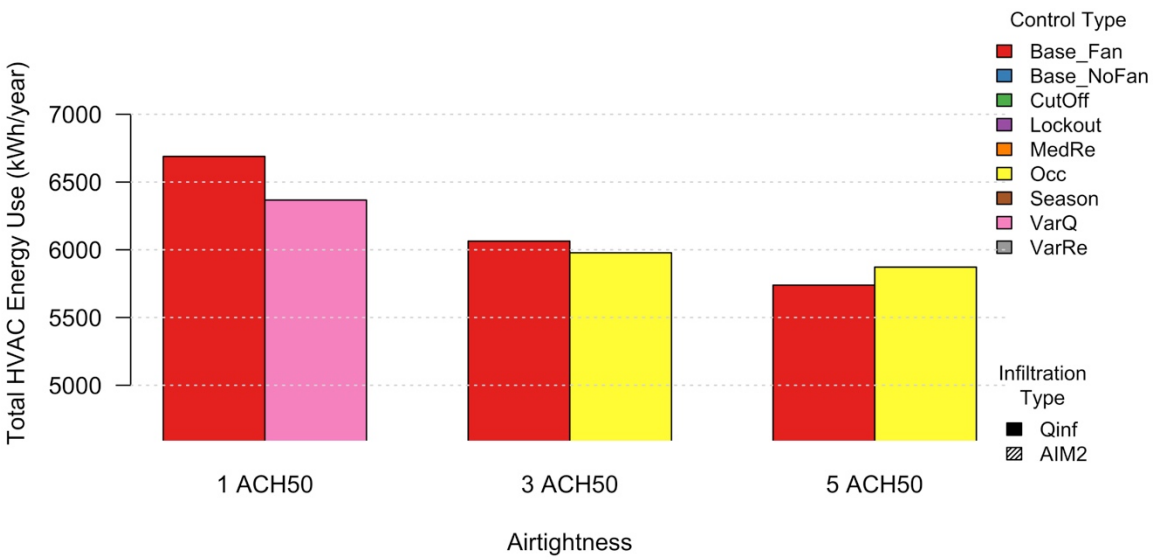


Figure 83 Total HVAC energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 1-story simulations in CZ1 (Arcata).

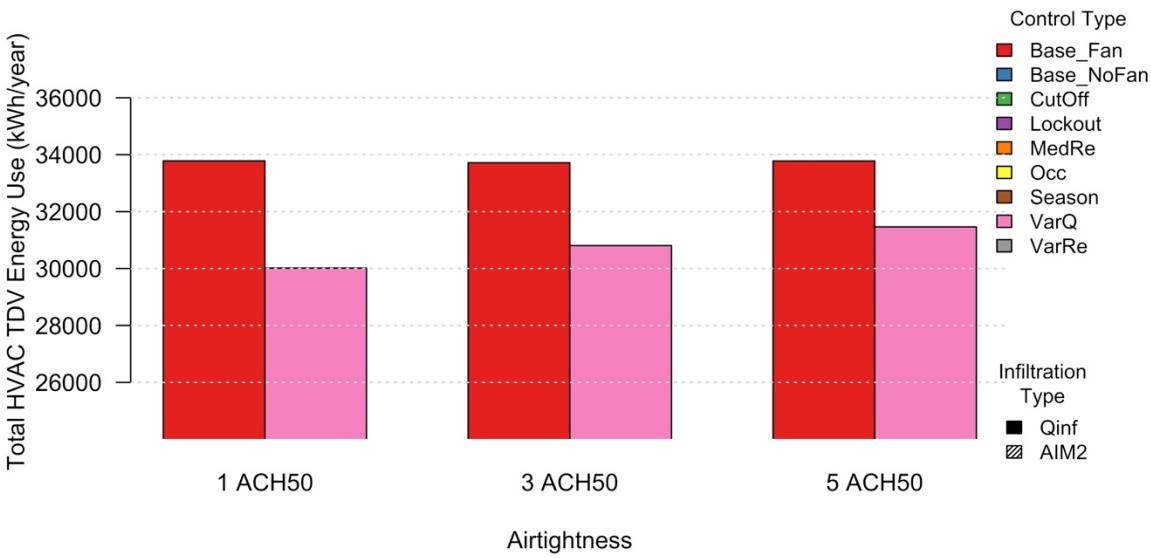


Figure 84 Total HVAC TDV energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 2-story simulations in CZ10 (Riverside).

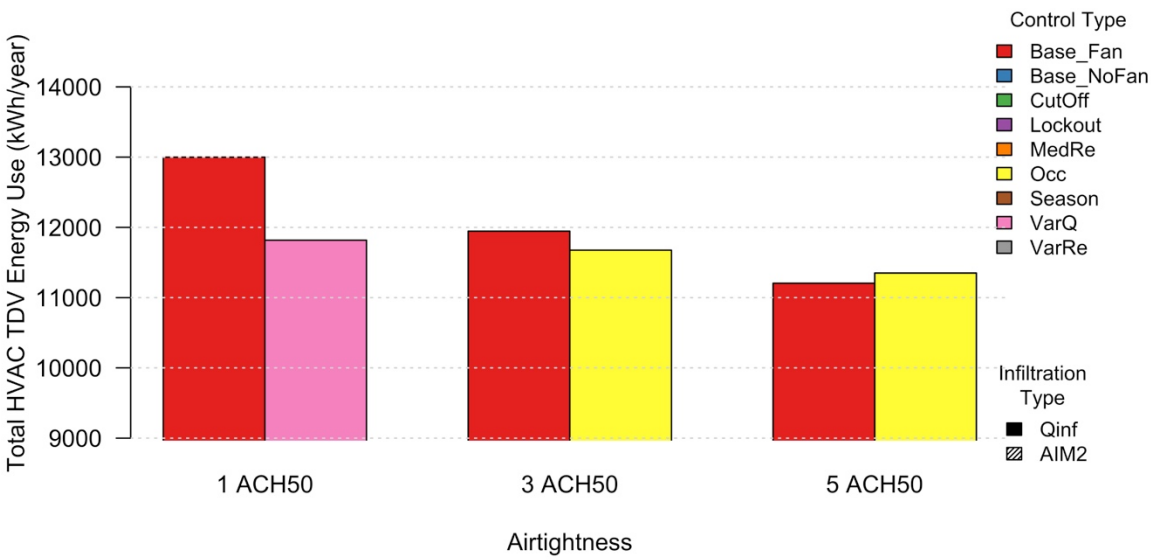


Figure 85 Total HVAC TDV energy use for the baseline fan and best-performing smart control type at each level of airtightness. Compliant cases, 1-story simulations in CZ1 (Arcata).

6.8 Title 24 Next Steps

The 2019 Title 24 has adopted parts of the ASHRAE 62.2-2016 ventilation standard, including the ability to demonstrate compliance for time-varying ventilation using relative exposure (i.e., smart ventilation controls in Normative Appendix C). But there is no current method in the Title 24 to account for the energy savings or to get compliance credit for such systems.

One option would be to incorporate the ability to model dynamic ventilation systems and relative exposure into CBECC-Res, or allow the use of pre-calculated

scheduled mechanical ventilation airflows (rather than the current fixed fan airflow). This is required to reflect the diversity of results found across house types, climates and envelope leakage rates in our work. This is also the only way to provide adequate market flexibility for future changes to control schemas by manufacturers, new code requirements, etc.

Another option is to use third-party compliance verification where a particular SVC approach is simulated using agreed upon assumptions and scenarios and gets an energy use multiplier that can be used in compliance calculations. The Energy Commission would also need to develop requirements or guidelines for manufacturers to use in demonstrating the compliance of their systems with the code requirements. This would include which housing types to model, ventilation system types, climate regions, and other such variables.

Notably, the reference case in our simulations was a continuous fan sized to the ASHRAE 62.2-2016 ventilation standard, but the 2019 Title 24 will require that IAQ fans in residences are sized differently. The new Title 24 fan sizing method is the same as ASHRAE 62.2-2016, but it fixes the envelope airtightness used in predicting annual effective infiltration at 2 ACH_{50} for all homes (homes that are tested below 2 ACH_{50} must use the lower number and increase the required fan size). Overall, this will increase the baseline fan sizes compared with our current simulations. This represents an additional opportunity for smart ventilation controls, because they can demonstrate energy savings relative to a baseline with higher ventilation energy consumption. Energy savings will increase, though improvements in IAQ through smart controls will be reduced or eliminated.

Finally, as discussed in Section 6.2, the superposition models used in ASHRAE 62.2-2016 are biased towards high exposure in constant fan cases using unbalanced fans. We suggest that this be fixed in ASHRAE 62.2 itself, but absent that, the CEC could consider amending the calculation procedures used in California. Specifically, we would recommend the equation used to estimate whole house airflow for exposure calculations in Normative Appendix C of the Standard be changed so that it is an identify (i.e., the same forwards-backwards) with the fan sizing equation. As outlined in Hurel, Sherman, & Walker (2015) Table 3, if the fan sizing superposition method currently in 62.2-2016 is used (i.e., Simple inverse sub-additivity) the matching forward calculation method should be used to estimate whole house airflows, as follows:

$$Q_{tot} = \frac{Q_{fan}}{2} + \sqrt{\frac{{Q_{fan}}^2}{4} + {Q_{inf}}^2} \quad (8)$$

7 Summary

Controller performance varied substantially by climate zone, airtightness and house prototype, therefore we cannot provide simple state-wide estimates of energy savings, nor can we identify which controllers are best optimized for state-wide use. Instead we were able to provide guidance on which control approaches are best suited to different climates.

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The most successful smart controls shifted ventilation rates seasonally, rather than over the course of the day or month and used parameters pre-calculated using an optimization routine, and they reduced weighted average site ventilation energy use by 31-39% (370-465 kWh/year; 8-11% of whole house HVAC energy), while TDV weighted average ventilation energy reductions were higher, at 31-64% (1,235-2,654 kWh/year; 5-10% of whole house TDV HVAC energy). Peak demand during the 2-6pm period on the hottest days of the year was reduced through use of the smart controls, with peak load reductions of 0-400 watts. We believe that specific peak controls could achieve even greater reductions in demand. The vast majority of site energy savings were for heating end-uses (>90% of total savings), while TDV energy savings were split fairly evenly between heating and cooling. On average, the smart controls reduced occupant pollutant exposure by 0-10% (improved IAQ), but they increased peak exposure to the occupants, with some controls having much higher peaks than others.

Smart ventilation and baseline constant fan cases did not provide the same IAQ. To provide an apples-to-apples assessment of energy savings, we normalized the energy use in each case by the corresponding annual relative exposure. When normalized, weighted average energy savings increased. The best controls achieved weighted average site ventilation energy savings of 48-55% (561-651 kWh/year; 13-15% whole house HVAC savings), and TDV ventilation savings from 46 to 72% (1900-2950 kWh/year; 7-11% whole house HVAC TDV savings).

Occupancy-based controls saved energy by reducing the whole house ventilation rate, but these controls were generally ineffective, with very low energy savings. Performance was improved somewhat through use of a 1-hour pre-occupancy flush out period, though savings were still marginal compared to temperature-based controls.

Auxiliary fan sensing increased site energy savings in all cases, from roughly 5 to 15%, with smaller increases in the highest performing control cases. This procedure increased the average non-normalized site ventilation savings for the best control types to a range between 40 and 48% (TDV ventilation savings between 40 and 65%).

Use of the smart ventilation controls was much more effective than increasing airtightness while using continuous fans sized to ASHRAE 62.2-2016, because the ventilation standard increases the required IAQ fan airflow, as infiltration is

reduced. This limits the benefits of air sealing and we would not recommend that the state adopt air tightness requirements.

Current products available for $150 to $300 on the consumer market have the core hardware capabilities to act as smart ventilation controls (fans or wall controllers with integrated temperature and humidity sensors), but none of the currently available products actually ensure compliance with the ASHRAE ventilation standard. More work is required in order to allow builders and designers to take credit for smart ventilation control strategies in demonstrating compliance with California' Title 24 Building Energy Code. Also, field demonstrations of the energy and IAQ performance of smart ventilation controls are needed in new California homes, before these technologies can be adopted at scale.

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9 Appendices

Appendix A Lock-Out (Lockout) Control Description

The lockout TSVC controls the ventilation fan based on the relatively predictable diurnal variation in outside dry bulb temperature, experienced across climate zones, based on patterns of solar irradiation. Using pre-calculated estimates, this smart controller turns the ventilation fan off during the hottest or coldest hours of the day (depending on season). The ventilation airflow is increased during all other hours of the day to ensure equivalence with a continuous fan (see Table 9). The lockout period (coldest vs. hottest hours) is selected each day based on the CEC definition of heating and cooling seasons.

Time Period	***Fan ON***
Lockout	OFF
Non-Lockout	ON

Table 9 Lockout TSVC control strategy.

To calculate the best hours to turn the ventilation fan off, we used all 16 CBECC weather files for the representative California locations. We used the following method. For each month of the year (1:12), an average outside temperature was calculated for each hour of the day (0:23), resulting in 288 values (12*24). This was done for each of 16 climate zones. We then sorted the hourly average temperatures for each month from lowest and highest, and we categorized the lowest and highest hours for every month and climate zone. The hours that occurred most frequently in the low and high categories were selected for the lockouts in Table 1.

Time Period	***Coldest Hours***	***Hottest Hours***
4-Hour	03:00 – 07:00	13:00 – 17:00
6-Hour	02:00 – 08:00	12:00 – 18:00
8-Hour	00:00 – 08:00	11:00 – 19:00

Table 10 Coldest and hottest 4-, 6- and 8-hour periods in each day. Used in TSVC lockout strategy.

Figure 86 shows the relative exposure, relative dose and outside temperature for an example temperature lockout strategy in a Arcata, CA (CZ1) two-story prototype home at 1 ACH_{50}. The lockout period is highlighted in pink. As expected, the relative exposure climbs quickly during the lockout period, up to peak around 1.8. Then the over-sized ventilation fan operates continuously during all other hours, bringing the relative dose to roughly 0.97, which reflects the integrated exposure over the prior 24-hours.

The exact size of the ventilation fan was pre-calculated for each case such that if operated continuously, the daily average relative exposure would be less than 0.97. This pre-calculation requires information about the house size, estimated infiltration (e.g., Q_{inf} from 62.2) and baseline fan airflow. Pre-calculation was performed for all CEC climate zones and

prototypes that we assessed, the required fan size multipliers (relative to the baseline 62.2 IAQ fan airflow) are provided in Table 11.

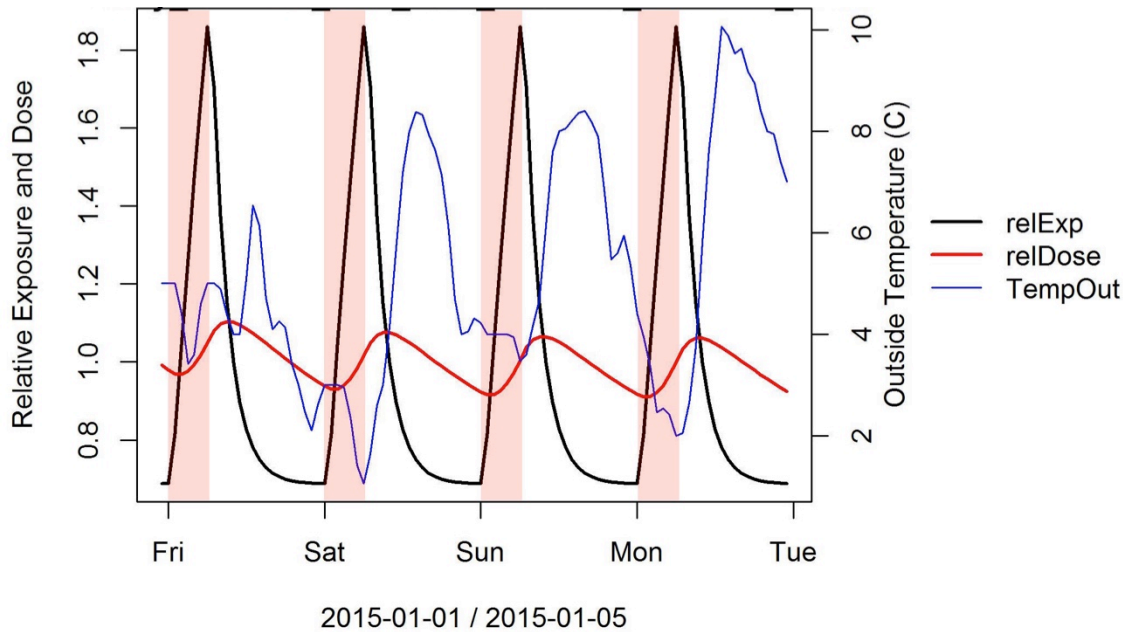

Figure 86 Illustration of the lockout control in 2-story, 1 ACH_{50} home in CZ1. Six-hour lockout period highlighted in pink.

			Lockout Period (hours)		
CZ	***Prototype***	***Airtightness (ACH_{50})***	***4***	***6***	***8***
1	1story	1	1.35	1.65	2.2
1	1story	3	1.3	1.5	1.8
1	1story	5	1.35	1.5	1.75
1	2story	1	1.35	1.6	2.1
1	2story	3	1.3	1.5	1.75
1	2story	5	1.55	1.7	1.9
3	1story	1	1.35	1.65	2.2
3	1story	3	1.3	1.5	1.8
3	1story	5	1.35	1.5	1.75
3	2story	1	1.35	1.6	2.1
3	2story	3	1.3	1.5	1.75
3	2story	5	1.5	1.65	1.85
10	1story	1	1.35	1.65	2.25
10	1story	3	1.3	1.55	1.9
10	1story	5	1.3	1.5	1.75
10	2story	1	1.35	1.65	2.1
10	2story	3	1.3	1.5	1.8
10	2story	5	1.35	1.5	1.75
16	1story	1	1.35	1.65	2.25

16	1story	3	1.3	1.5	1.9
16	1story	5	1.3	1.5	1.75
16	2story	1	1.35	1.65	2.1
16	2story	3	1.3	1.5	1.75
16	2story	5	1.4	1.55	1.75

Table 11 Table of fan size multipliers for use with 4-, 6- and 8-hour lockout controls.

Appendix B Running Median (MedRe) Control Description

This smart control targets custom high and low relative exposure values based on comparing the current outside temperature (T_i) to its running median value ($T_{rollmedian}$). When in heating season and it is currently colder than the running median, the ventilation is reduced (target RE_{high}), otherwise it is increased (target RE_{low}). Vice versa in the cooling season. The relative exposure values should be equidistant from 1.0. For example, 0.5 and 1.5, or 0.4 and 1.6. The maximum appropriate values can be calculated using the smart fan-oversizing fraction ($F_{oversize}$) using Equations 9 and 10. The control conditions are outlined in Table 12. As a reminder, there is no direct control based on daily integrated exposure (i.e., relative dose) in this strategy, the controller simply targets either the high and low exposure targets. The running median will provide the temperature at which we expect an equal number of hours at each exposure target. This should allow the controller to maintain average relative exposure very close to one.

The value in this approach would be the controller's ability to shift ventilation between time periods, depending on the length of the running median period. The lockout control approach described in Section 3.1.1 allows shifting of ventilation between hours of the day. The running median approach allows shifting within hours of the day, as well as between days, weeks or months that are overall warmer or cooler. A running median period of 7-days allows shifting between days. A 30-day running median period allows shifting of ventilation between weeks. Finally, using the annual median as the control point allows shifting of ventilation between months/seasons. We expect greater energy savings with longer running median periods, but this may come at the cost of failing to maintain relative exposure below one on an annual basis.

Season	***High Relative Exposure Target Condition***
Heating	$T_i < T_{rollmedian}$
Cooling	$T_i > T_{rollmedian}$

Table 12 Control for running median TSVC.

$$\boldsymbol{RE_{high} = 1 + \left[1 - \frac{1}{F_{oversize}}\right]} \quad \textbf{(9)}$$

$$\boldsymbol{RE_{low} = \frac{1}{F_{oversize}}} \quad \textbf{(10)}$$

We assessed this running median approach by analyzing weather data for all 16 CEC climate zones using rolling median periods of 3-, 7-, 14- and 30-days (all right-adjusted, such that no "future" data was included in the median calculation). For each location, we calculated the running median outside temperature and compared this with the real-time dry bulb temperature. During the heating, if the real-time value was less than the running median, then we assigned a relExp target of 1.5 (under-venting due to cold weather), and if the real-time temperature was above the running median, then we targeted 0.5 (over-venting due to warm weather). The opposite relationships were used during the cooling season. We then calculated the annual average exposure using these assignments. The annual mean relative exposures for each climate zone and running median time period are listed in Table 13. The average across climate zones is at the bottom of the table. Notably, these values are simple estimates and will not match exactly those from our real-time simulations. This is because it takes time for the real-time relExp to travel between the low and high target values (i.e., the change from 1.5 to 0.5 is not instantaneous), and it increases and decreases at different rates depending on the direction.

As the rolling median period grew longer, this approach lost the ability to provide estimated annual relative exposures below one. We believe this occurred, because the longer time periods are not sufficiently representative of the temperatures that will occur in the future, so the median is no longer a reliable control parameter. The prior three days is a better predictor of the following three days, than the prior month is a predictor of the next month. The 7-day period was the longest rolling period with acceptable expected performance across all CA climates. The 14-day had marginal performance in many locations, though it is close enough that we believe it is worth testing with full simulations. The 30-day period was higher still. We have simulated only the 30-day running median period, as we expect it to have the greatest energy savings.

	Annual Average Relative Exposure Estimate Running Median Control			
Climate Zone	***3-day***	***7-day***	***14-day***	***30-day***
1	0.948	0.949	0.947	0.900
2	0.987	0.990	0.999	1.014
3	0.975	0.974	0.994	1.016
4	0.990	0.994	0.999	1.016
5	0.977	0.979	0.989	1.002
6	0.997	0.998	1.003	1.020
7	1.002	0.998	1.024	1.054
8	1.003	0.999	1.026	1.038
9	0.986	0.992	1.025	1.045
10	0.998	1.001	1.018	1.033
11	0.977	0.980	0.991	1.016
12	0.987	0.988	0.997	1.022
13	0.982	0.991	0.999	1.030
14	0.985	0.980	0.992	1.013

15	0.984	0.977	1.016	1.037
16	0.987	0.996	1.020	1.050
Average	*0.985*	*0.987*	*1.002*	*1.019*

Table 13 Annual average relative exposure values for each CEC Climate Zone based on simple relative exposure targets.

Appendix CSeasonal Control (Season) Control Description

Another TSVC approach is to control to different average relative exposure targets depending on the season. Based on our past work, reducing the ventilation rate during the heating season (and increasing it during cooling season) has a net-energy benefit. So, for a seasonal controller, we target higher average exposure during heating season (reduced ventilation rate) and lower exposure during cooling season (higher ventilation rates). The ASHRAE ventilation standard requires the annual average relative exposure to be less than one to be compliant. So, high and low exposure targets can be calculated for any climate zone using a weighted average approach that should provide an annual average very close to one.

We begin by selecting a heating season mean relative exposure target ($RE_{mean,heating}$). Equation 11 is then used to calculate a corresponding cooling season mean exposure target ($RE_{mean,cooling}$) that maintains the annual average exposure less than the annual exposure target (RE_{annual}, typically 1 or 0.97). We used an RE_{annual} value of 0.97 in calculating our control parameters in our simulations. The cooling exposure target depends on the fraction of annual hours spent in the heating season (f_{heat}). If the required cooling season target is less than $1/F_{oversize}$, then annual equivalence is impossible. In Table 15, we provide pre-calculated f_{heat} values for each climate zone and the associated mean cooling season RE targets for each climate zone based on heating season targets from 1 to 1.5 (we used an annual exposure target of 0.97 to derive these cooling targets). As heating season mean increases, the cooling mean must go down. When the $RE_{mean,cooling}$ target is less than $1/F_{oversize}$, the controller will not have annual exposure less than one. To aid in compliance for the Seasonal controls, the fans were additionally oversized, with $F_{oversize}$ set to equal 1.2 / $RE_{mean,cooling}$. For all climate zones except CZ10, we only simulated the highest $RE_{mean,heating}$ value where the corresponding $C_{mean,cooling}$ value was greater than 0.5 (roughly an $F_{oversize}$ of 2). For example, in CZ3 the highest $RE_{mean,heating}$ value we simulated was 1.2, because 1.3 required an $RE_{mean,cooling}$ of 0.383. For CZ10, we simulated all cases with $RE_{mean,heating}$ 1.2 to 1.5.

$$\boldsymbol{RE_{mean,cooling}} = \frac{[(\boldsymbol{RE_{annual}} - \boldsymbol{RE_{mean,heating}} \times \boldsymbol{f_{heat}}]}{(\mathbf{1} - \boldsymbol{f_{heat}})} \quad \textbf{(11)}$$

RE_{annual} = annual relative exposure target (e.g., 1 or 0.97 or as desired)
$RE_{mean,cooling}$ = mean relative exposure target during all cooling season hours
$RE_{mean,heating}$ = mean relative exposure target during all heating season hours
f_{heat} = fraction of annual hours that are heating season

Season	*Fan ON Condition*
Heating Season	relExp > $RE_{mean,cooling}$
Cooling Season	relExp > $RE_{mean,heating}$

Table 14 Control states for the Seasonal TSVC.

CZ	*Heating Season Fraction (f_{heat})*	*Cooling Season Mean RE Targets for Each Heating Season Target*					
		1	*1.1*	*1.2*	*1.3*	*1.4*	*1.5*
1	1	NA	NA	NA	NA	NA	NA
2	0.592	0.926	0.781	0.636	0.491	0.346	0.201
3	0.640	0.917	0.739	0.561	0.383	0.205	0.027
4	0.525	0.937	0.826	0.715	0.605	0.494	0.383
5	0.813	0.840	0.406	-0.028	-0.462	-0.895	-1.329
6	0.476	0.943	0.852	0.761	0.670	0.580	0.489
7	0.415	0.949	0.878	0.807	0.736	0.665	0.594
8	0.376	0.952	0.892	0.831	0.771	0.711	0.651
9	0.400	0.950	0.883	0.817	0.750	0.684	0.617
10	0.435	0.947	0.870	0.793	0.716	0.639	0.562
11	0.521	0.937	0.829	0.720	0.612	0.503	0.394
12	0.515	0.938	0.832	0.726	0.620	0.514	0.408
13	0.485	0.942	0.848	0.754	0.660	0.566	0.472
14	0.516	0.938	0.832	0.725	0.619	0.512	0.406
15	0.208	0.962	0.936	0.910	0.883	0.857	0.831
16	0.650	0.914	0.728	0.542	0.357	0.171	-0.015

Table 15 Cooling season mean RE targets for each CZ, varying heating season targets, annual exposure target of 0.97.

Appendix D Cut-Off Temperature Control (CutOff) Control Description

Past work on temperature controlled smart ventilation suggested that a simple cut-off temperature was an effective approach to reducing ventilation load through smart control (Less et al., 2014). In this work, we developed a more complicated cut-off approach that ensures annual relative exposure less than one using a weighted average approach and parametric optimization (as in the Seasonal controller).

Heating and cooling season exposure targets (H_{mean} and C_{mean}) are calculated using the same weighted average method described for the seasonal controller. Then low and high exposure targets are developed that are the same in both seasons. The low RE target is always dependent on the fan over-sizing ($1/F_{oversize}$). The high exposure target (RE_{max}) and the cut-off temperatures for each season are determined by parametric optimization coded in R. For each climate zone, we assessed relative exposure and annual ventilation load for heating season mean exposure targets varying from 1 to 2 by increments of 0.1. For each heating season mean value, we tested high exposure targets (identical for heating and

cooling) from 1 to 3 by increments of 0.1, and we assessed heating and cooling cutoff temperatures spanning the entire range of seasonal outdoor temperatures by 0.5°C increments. Annually, we selected the parameters that minimized the ventilation energy use, while maintaining estimated annual exposure below 0.97. Ventilation energy use was estimated using a simplified Q*rho*cp*dT approach, with airflow estimated as Q_{tot}/RE_{target}. Ventilation load was translated to site energy assuming a 95% efficient gas heater and an air conditioner with EER of 12.8. Free heating or free cooling were not allowed to offset ventilation load. No fan energy or air handler energy estimates were included.

Depending on the season, the controller selects either the high or the low exposure target, based on the current temperature (T_i) and the cut-off temperature (T_{cutoff}). The control logic is summarized in Table 16.

Season	RE_{high}	RE_{low} $(1/F_{oversize})$
Heating	$T_i < T_{cutoff}$	$T_i > T_{cutoff}$
Cooling	$T_i > T_{cutoff}$	$T_i < T_{cutoff}$

Table 16 Control states for the temperature cut-off control.

An example optimization output is pictured in Figure 87 for CZ10 (Riverside) assuming a fan oversizing of 2. We show estimated ventilation energy use (y-axis) compared with maximum exposure values (x-axis) for a variety of heating season mean values (different colored lines). We see that for this climate zone, the energy use is minimized when the heating season mean is 1.5 and the high exposure target is 1.8. Estimated savings in this scenario are 36% of the ventilation load. We ran this optimization routine for every climate zone in California using a fan multiplier of 2, and the control parameters are listed in Table 17 (See Table 18 for optimized parameters with fan multiplier of 3). The controller only requires four parameters—$T_{cutoff,heating}$, $T_{cutoff,cooling}$, RE_{max} and $F_{oversize}$.

The optimization tended to select cutoff temperatures where the house airflow would be reduced for the maximum number of hours. This suggests that small reductions in ventilation rate over greater numbers of hours are more effective than greater reductions in ventilation rate over fewer hours. In general, the high exposure targets were only a few tenths greater than the heating season average exposure targets, meaning that this approach will limit peak exposure quite well.

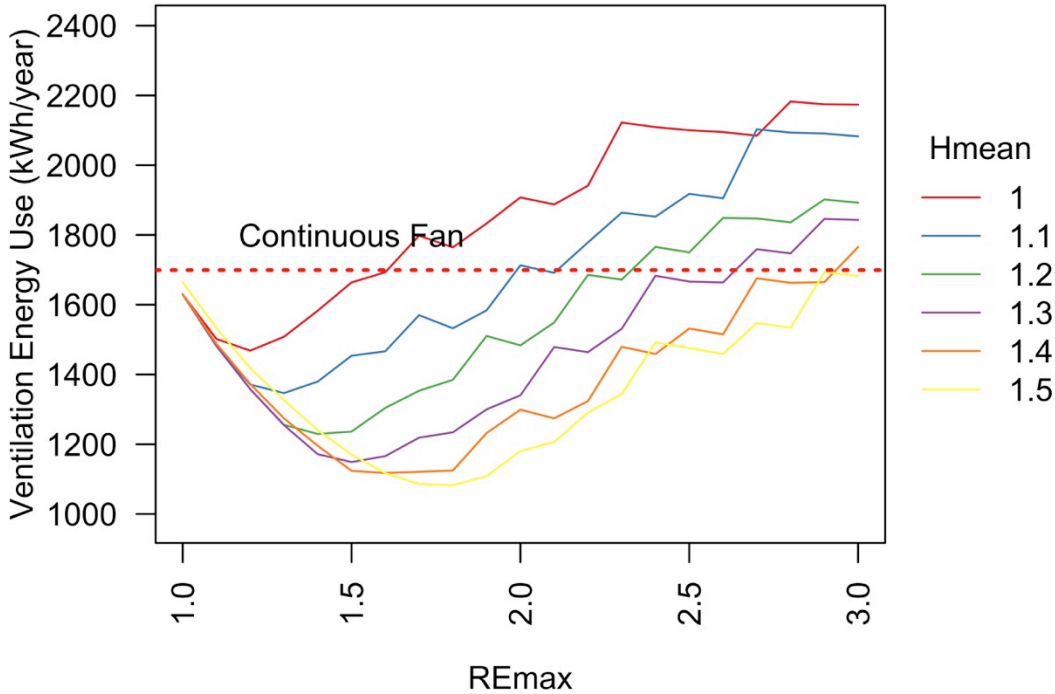

Figure 87 Example of parametric optimization results for CZ10, using the Cutoff control. Optimum is H_{mean} of 1.5, RE_{max} of 1.8 with estimated site energy savings of 36% (assuming $F_{oversize}$ of 2).

CZ	H_{mean}	C_{mean}	RE_{max}	$T_{cutoff,heat}$	$T_{cutoff,cool}$	*Estimated Site Energy Savings (%)*
1	1	NA	1	31.5	NA	4
2	1.2	0.64	1.3	16.7	26.5	24
3	1.2	0.56	1.3	15.6	22.5	20
4	1.3	0.60	1.4	17	26.9	29
5	1	0.84	1.1	17.1	14.1	10
6	1.4	0.58	1.6	16.9	24.5	36
7	1.6	0.52	1.7	17.5	24.9	42
8	1.7	0.53	1.9	17.9	30.9	46
9	1.6	0.55	1.8	17.4	32.5	41
10	1.5	0.56	1.8	16.5	34.1	36
11	1.4	0.50	1.5	17.4	41.7	26
12	1.4	0.51	1.5	16.9	36.9	30
13	1.4	0.57	1.5	16.4	36.1	27
14	1.4	0.51	1.6	15.5	39	28
15	1.3	0.88	1.5	18	30	31
16	1.2	0.54	1.3	13	26.8	21

Table 17 Optimized cutoff control parameters with $F_{oversize}$ = 2.

CZ	H_{mean}	C_{mean}	RE_{max}	$T_{cutoff,heat}$	$T_{cutoff,cool}$	Estimated Site Energy Savings (%)
1	1	NA	1	31.5	NA	4
2	1.4	0.35	1.5	18.2	35.5	32
3	1.3	0.38	1.4	16.6	23.5	26
4	1.5	0.38	1.6	18	30.4	37
5	1.1	0.41	1.2	18.1	22.1	18
6	1.6	0.40	1.7	18.9	25.5	43
7	1.8	0.38	1.9	18	23.9	48
8	1.9	0.41	2.1	18.9	28.9	52
9	1.8	0.42	2	18.4	32	45
10	1.6	0.48	1.8	18.5	32.1	39
11	1.4	0.50	1.5	17.9	33.7	28
12	1.5	0.41	1.6	17.9	33.9	33
13	1.5	0.47	1.6	17.4	34.6	29
14	1.4	0.51	1.5	18.5	33.5	29
15	1.4	0.86	1.6	19	29	34
16	1.3	0.36	1.4	14	28.3	25

Table 18 Optimized cutoff control parameters with $F_{oversize}$ = 3.

Appendix E Optimized Variable Airflow (VarQ) Control Description

We also tested continuously variable airflow TSVC controllers that scale the target ventilation airflow or relative exposure based on the current inside-outside temperature difference. These include the VarQ and VarRe control types, described here and in Appendix F. These proportional controllers shift ventilation away from periods of large indoor-outdoor temperature difference to mild or even beneficial time periods. A variable airflow controller can use either a variable airflow fan or it can schedule a fixed-speed fan to cycle in order to achieve varying average flows over some short period (e.g., 20 minutes). Both proportional controllers use the f-scale calculation shown in Equation 12, which compares the current temperature difference ($T_i - T_{therm}$) against the Seasonal maximum temperature difference ($T_{max} - T_{therm}$). The value is bounded between 0 and 1, and it is multiplied by either a ventilation airflow or a peak relative exposure target.

$$f_{scale} = 0 \leq \left[1 - \frac{(T_i - T_{therm})}{(T_{max} - T_{therm})}\right] \leq 1 \quad (12)$$

T_i = current outdoor temperature, °C
T_{therm} = thermostat setting, °C
T_{max} = seasonal maximum temperature (hottest or coldest, by season), °C

T_{max} is a seasonal value representing the coldest expected temperature during the heating season and the warmest expected temperature during the cooling season (see Table 19 for these values for each CEC climate zone, calculated from CBECC-Res weather files). The f-

scale factor is calculated once each time-step. An illustration of the f-scale value is plotted for heating (black line) and cooling (red line) seasons in Figure 88. This is illustrative only and does not reflect temperatures from a CEC climate zone.

Climate Zone	***Annual Minimum Temperature (°F)*** T_{max} ***- Heating***	***Annual Maximum Temperatures (°F)*** T_{max} ***- Cooling***
1	29	81
2	27	103
3	31	91
4	15	99
5	29	87
6	25	102
7	41	90
8	34	105
9	34	107
10	29	109
11	28	113
12	28	109
13	30	108
14	20	106
15	36	115
16	17	90

Table 19 T_{max}, annual minimum and maximum outdoor temperatures for each CEC climate zone.

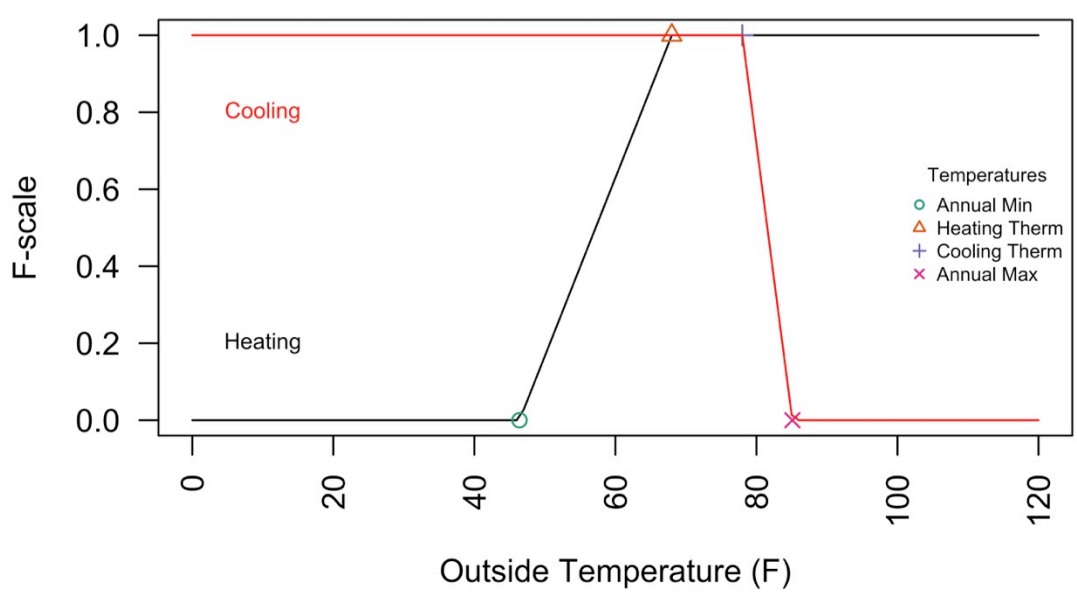

Figure 88 F-scale factors for proportional temperature control in heating (black) and cooling (red) seasons.

The VarQ TSVC uses this f-scale factor and multiplies it by the smart ventilation fan maximum airflow as in Equation 13. This scales the target fan airflow between 0 (off) and

the maximum, which is the two-times the baseline continuous ventilation fan airflow. We illustrate the resulting airflows across a range of outside temperatures in Figure 7. The heating season airflow (black line) is set to 0 when outside temperature is below the T_{max} value (roughly 45°F here), it scales fan airflow linearly up to the maximum airflow when outside air is the same as the thermostat setting (65°F), and the fan airflow remains at maximum at all temperatures warmer than the thermostat setting (free heating). The opposite happens in cooling season (see the red line), again taking advantage of free cooling whenever possible.

$$\boldsymbol{Q_i = Q_{fan} \times f_{scale}} \tag{13}$$

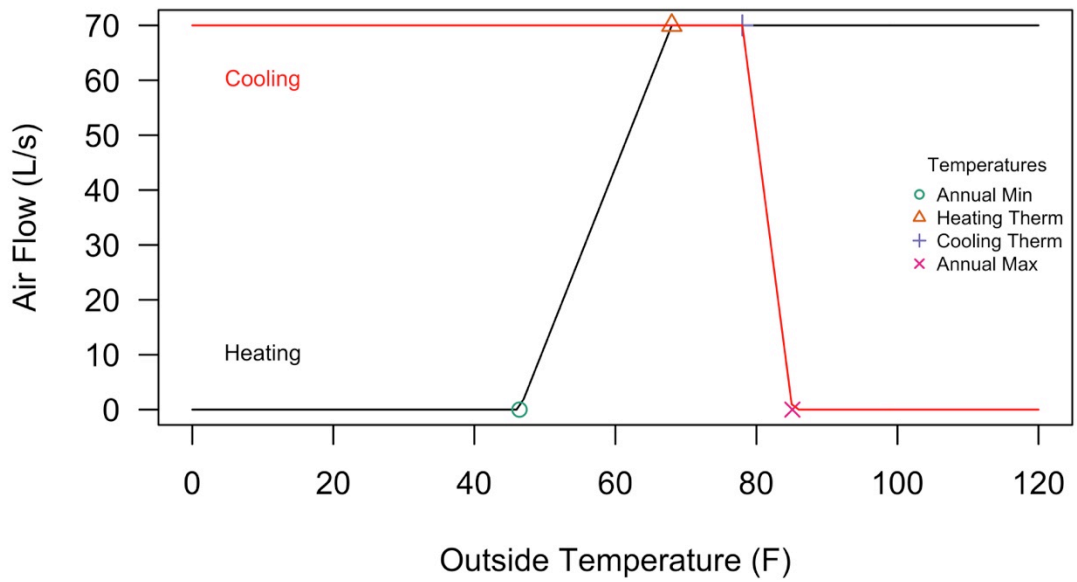

Figure 89 Example airflows for a 70 L/s smart ventilation fan in heating (black) and cooling (red) seasons, generated using F-scale factor across range of outside temperatures.

For a given distribution of outside temperatures in a given climate, there is no guarantee that using the seasonal hottest and coldest temperatures for T_{max} will give an annual relative exposure less than or equal to 1. Using CEC weather data, we pre-calculated the annual relative exposure that this strategy would provide for each case, using prototype house data and estimates of infiltration (Q_{inf}) and fan airflows. In nearly all CEC climate zones, this resulted in an annual estimated exposure substantially below one. So, this approach would over-ventilate most homes and was not optimized from an energy perspective.

We determined that the VarQ control did not necessarily need to scale down to the seasonal maximum or minimum temperatures, rather the $T_{max,heating}$ value could be increased above the annual minimum temperature, and the $T_{max,cooling}$ value could be decreased below the annual maximum temperature (see Equations 14 and 15). Ventilation energy is reduced the more these values are increased/decreased above/below the annual max/min temperatures, subject to the requirement that exposure must be estimated to be

less than 0.97. In essence, the sloped lines in Figure 89 would become more vertical, further reducing ventilation airflow during hot/cold periods. We refer to the increase/decrease as T_{offset}.

T_{offset} was determined numerically by parametric optimization coded in R. We simplified this optimization problem by forcing T_{offset} to be the same in heating and cooling seasons. Optimization of the seasons independently from one another could offer marginally improved control performance. Optimization targeted the largest T_{offset} value that still satisfied the relative exposure requirement (annual RE < 0.97). As T_{offset} increases, so do energy savings and annual exposure. For each case, we calculated the appropriate $T_{max,heating}$ and $T_{max,cooling}$ values. The optimal control parameters used in our simulations are provided in Table 20. The T_{offset} values varied substantially by climate zone, but were reasonably consistent across house parameters (i.e., airtightness and size). While we did not do this in our simulations, one could select single representative $T_{max,heating}$ or $T_{max,cooling}$ values for each climate zone, so as to simplify this control specification. For example, in CZ3, we could reasonably say that $T_{max,heating}$ is 42°F for all cases, while $T_{max,cooling}$ is 79°F.

In order to perform these estimates on a generic home, a designer would need the weather data file, house size/volume information, baseline 62.2 fan airflow, fan size multiplier and infiltration estimates.

$$\boldsymbol{T_{max,heating} = T_{min,annual} + T_{offset}} \quad \textbf{(14)}$$

$$\boldsymbol{T_{max,cooling} = T_{max,annual} - T_{offset}} \quad \textbf{(15)}$$

Prototype	*Airtightness (ACH_{50})*	*CZ*	*$T_{max,heating}$ (°F)*	*$T_{max,cooling}$ (°F)*
1-story	1	1	31.58	77.6
1-story	3	1	31.58	77.6
1-story	5	1	30.58	78.6
2-story	1	1	31.58	77.6
2-story	3	1	31.58	77.6
2-story	5	1	21.58	87.6
1-story	1	3	41.56	80.22
1-story	3	3	42.56	79.22
1-story	5	3	43.56	78.22
2-story	1	3	41.56	80.22
2-story	3	3	43.56	78.22
2-story	5	3	41.56	80.22
1-story	1	10	43.76	94.4
1-story	3	10	44.76	93.4
1-story	5	10	46.76	91.4
2-story	1	10	43.76	94.4
2-story	3	10	45.76	92.4

2-story	5	10	47.76	90.4
1-story	1	16	19.24	87.96
1-story	3	16	20.24	86.96
1-story	5	16	21.24	85.96
2-story	1	16	19.24	87.96
2-story	3	16	20.24	86.96
2-story	5	16	21.24	85.96

Table 20 Parametrically optimized $T_{max,heating}$ and $T_{max,cooling}$ values for each case and climate zone, maintain annual relative exposure <=0.97. VarQ.

Appendix F Optimized Variable Relative Exposure (VarRe) Control Description

The same f-scale outside temperature approach detailed above can also be used with a variable relative exposure controller. The concepts are the same, but rather than targeting a certain airflow, a relative exposure value is targeted by the controller. The controller turns the ventilation fan on only when the real-time exposure exceeds the target exposure (see Table 21). It is notable, that this controller does not actively control daily integrated exposure (i.e., relative dose) to below one, rather the controller simply tries to maintain the target at each time-step. This means the targets need to be pre-calculated such that they will average less than one over the year.

Condition	***Fan Status***
$RE_i > RE_{target}$	ON
$RE_i <= RE_{target}$	OFF

Table 21 Control strategy for VarRe using the RE_{target} calculated at each time step.

Equation 16 shows how the relative exposure target (RE_{target}) is calculated at each time step, using f-scale, fan size multiplier and a maximum exposure target. $F_{oversize}$ is the fan size multiplier for the smart fan relative to the size of the 62.2-2016 fan (1.5 is 50% larger, 2.0 is 100% larger, etc.). This roughly fixes the minimum relative exposure value that can be targeted by a fan that is operated continuously ($1/F_{oversize}$). The RE_{max} value is the peak relative exposure allowed (ASHRAE 62.2-2016 allows a peak up to 5).

In the VarQ controller, the $T_{max,heating}$ and $T_{max,cooling}$ values were varied to optimize performance, but in the VarRe controller we used the annual T_{max} values (Table 19) and instead varied the maximum relative exposure targets to optimize energy performance. For each climate zone, we determined unique RE_{max} values independently for heating and cooling seasons, which minimized ventilation load while maintaining estimated exposure below 0.97. These RE_{max} values were estimated using parametric optimization implemented in R. The optimum was selected as the combination of heating and cooling season RE_{max} values that minimized the net-ventilation load (Q*rho*cp*dT), while having an annual mean relative exposure less than 0.97. Unlike in the VarQ optimization, here we independently treated the $RE_{max,heating}$ and $RE_{max,cooling}$ values, varying each value between 1 and 5, by increments of 0.1. Optimized VarRe control parameters are provided for each CEC climate zone in Table 22 based on the assumption of a fan size multiplier of two (smaller or

larger fans would require different optimized control parameters). The results are independent of house type/size, airtightness, etc., which makes estimation of the control parameters less burdensome on the user.

$$RE_{target} = \left[RE_{max} - \left[RE_{max} - \frac{1}{F_{oversize}}\right] \times f_{scale}\right] \quad (16)$$

CZ	Optimized RE_{max} Values	
	Heating	Cooling
1	1.5	1.5
2	2.5	1.75
3	2.5	5
4	3.75	1.75
5	2.25	5
6	4.5	5
7	4	5
8	4.75	1.5
9	4	1
10	3.75	1.5
11	2.5	1.25
12	2.75	1
13	2.5	1.25
14	2.75	1
15	4.5	1.75
16	2	2

Table 22 Optimized RE_{max} values for heating and cooling season for each CEC Climate zone, assuming an IAQ fan with double the 62.2 airflow requirement.

An example VarRe control is plotted across a range of outside temperatures in Figure 90, showing the relative exposure target at each outside temperature. The RE_{max} values are different in heating (4.0) and cooling seasons (2.0), and you can see how the RE targets scale linearly between the thermostat setting and the annual minimum temperature in heating (or maximum temperature in cooling season). As with the VarQ control, in heating when outside air is above the thermostat setting, ventilation is increased to its maximum to get free heating (RE target of 0.5), vice versa in cooling season. The VarRe control is distinct from the VarQ in that it never fully tells the ventilation fan to shut off, rather a high exposure is targeted, such that ventilation airflow is reduced. We expect more variability in airflow and higher peak exposure for the VarQ control.

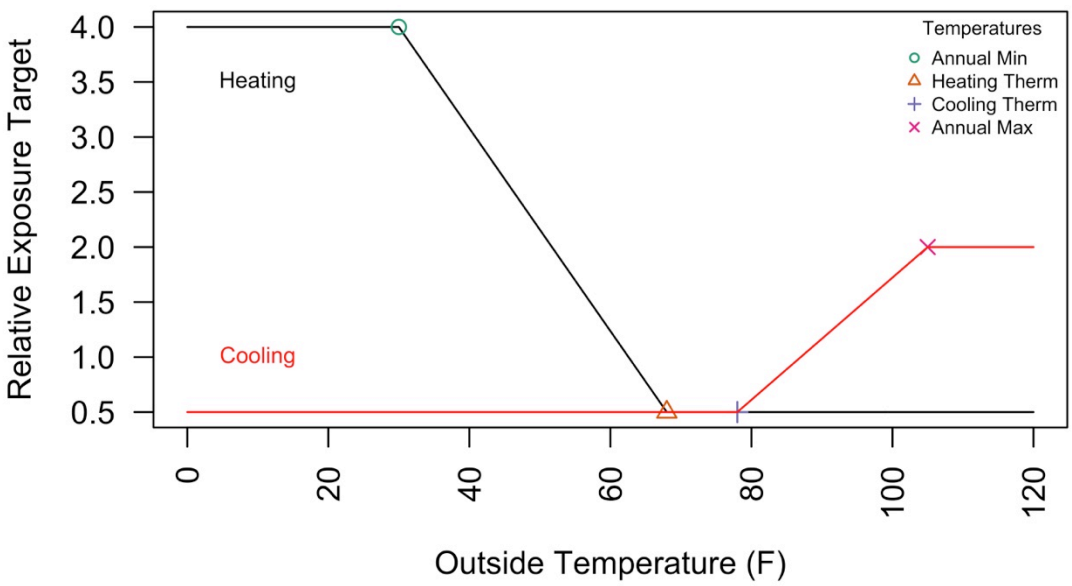

Figure 90 Relative exposure targets that vary continuously with outside temperature, using an RE_{max} values optimized independently for heating and cooling seasons.

Appendix G Occupancy Controls (Occ) Control Description

The Occupancy SVC is a real-time IAQ control that responds to the occupancy of the home and shuts off (or reduces to low speed) the ventilation fan during unoccupied periods. In this work, we assess the performance of three versions of an Occupancy SVC: (1) fan OFF during unoccupied periods, (2) fan on low speed during unoccupied periods, and (3) a version that flushes the house at a high ventilation rate one hour before occupancy. A control description for the first fan-off control is provided in Table 23, representing the basic Occupancy SVC. We focus on a common 1st shift occupancy pattern with a 9-hour weekday absence period and otherwise continuous occupancy. The operation of the control is described in the paragraphs below.

During the unoccupied period, the relative exposure is continually calculated and it is controlled to a maximum value of 5, as required by ASHRAE 62.2-2016. This maximum relative exposure is based on the acute to chronic concentration ratios for pollutants of concern. More details are available in M. H. Sherman, Logue, & Singer (2011) and Max H. Sherman et al. (2012). The IAQ fan can be turned off during unoccupied time periods, because the occupants are not exposed to the contaminants in the space. This is acceptable, as long as the controller accounts for the increased exposure the occupants receive when returning home after the ventilation system had been off.

During unoccupied periods, the relative dose is no longer calculated, and rather is fixed at its last occupied value. When occupants return home, relative dose is calculated again and quickly rises above one in response to the high relative exposure. The IAQ controller must increase the ventilation rate to bring relative exposure and relative dose below one. We

refer to this as the 'recovery period'. The duration of the recovery period is dependent on the IAQ fan size and the peak relative exposure reached during the unoccupied period.

An illustration of the Occupancy SVC is provided in Figure 9. The day begins with the IAQ fan turning on and off to cycle the relative exposure (*relExp*, red line) above and below 1. Exposure increases when the fan is off and decreases when the fan is turned on. Light grey highlighted periods show IAQ fan on periods, and the aqua region shows the unoccupied mid-day period. The relative dose (*relDose*, blue line) tracks the running average of the relative exposure and is fixed at almost exactly one. The unoccupied period is marked by relative exposure increasing to a peak around 2.7 when the occupants return home. The relative dose increases slightly when occupants return home, and it is reduced back below one during the recovery period. The IAQ fan is off during the entire unoccupied period, and then it is on continuously until the recovery period ends when both relative exposure and relative dose are less than one (approximately 23:00). This same pattern is repeated each day of the week with an occupant absence.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	relExp > 5

Table 23 Occupancy control strategy, fan off during unoccupied times.

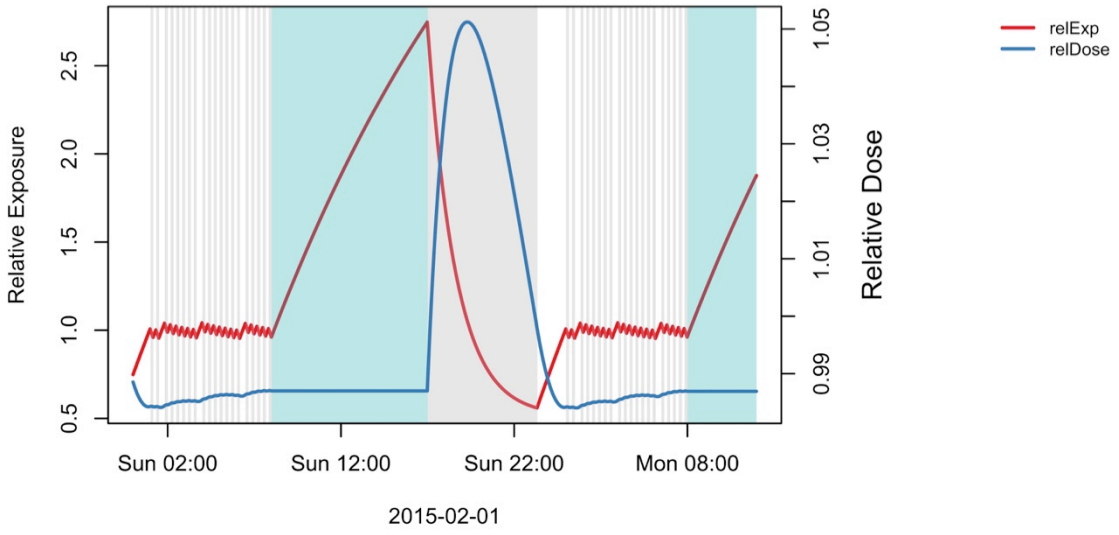

Figure 91 Illustration of Occupancy control operation with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

This occupancy SVC is distinguished from many other demand-controlled devices, which have historically used either relative humidity or CO_2 as indicators (Emmerich & Persily, 2001; Fisk & De Almeida, 1998; Raatschen, 1990). This approach assumes that occupancy is directly detected by any variety of methods, which could include IR motion sensors, smart phone network detection, smart meter analytics, simple timer-based scheduling, etc. Unlike the temperature-based controls described in the prior section, the occupancy

controller is intended to save energy by reducing the average ventilation rate of the home, while maintaining exposure less than one.

We will simulate one occupancy pattern, with 9-hour weekday absences from 8am to 5pm, representing a typical 1st shift workweek. Occupancy is continuous on weekends. While not simulated in this work, the model is also set-up to assess shorter and longer absence periods of 4- and 12-hours. The number of occupants at any given time will be unspecified and is unnecessary for this control strategy.

Low Fan Airflow While Unoccupied

As noted above, the ventilation fan will be treated in two different ways during the unoccupied period. First, the IAQ fan will be turned off during unoccupied times, subject to a relative exposure limit of 5 (see control description in Table 23). Second, the IAQ fan will be operated at a lower airflow that is some fraction of the ASHRAE 62.2 fan airflow (see control description in Table 24). Mortensen, Walker, & Sherman (2011) showed that for a variety of unoccupied periods, emission assumptions and constant fan airflows, the peak effectiveness of an occupancy controlled system occurred when the ventilation rate during unoccupied times was between 0.13 and 0.4 of the constant air volume system. Their results suggest that a value of roughly 0.35 will be appropriate for the cases we are simulating (i.e., fixed pollutant emission during both occupied and unoccupied hours, roughly 8-12 hour absence periods). As such, we will use this 0.35 as our target in these cases. We implement this by multiplying the continuous fan airflow by 0.35 during unoccupied time periods. This approach should reduce the peak exposure experienced everyday by the occupants, and it will hopefully reduce the average ventilation rate required to maintain exposure below one, thus saving energy.

Condition	***Fan ON Condition***
Occupied	relExp > 1 OR relDose > 1
Unoccupied	$Q_{fan} = 0.35 \times Q_{62.2}$

Table 24 Occupancy control strategy, fan at 35% of ASHRAE 62.2 continuous Q_{fan} airflow during unoccupied times.

A secondary, but still important effect, is the outdoor conditions during the unoccupied period. For example, the 1st shift occupancy pattern includes only daytime absences. During heating, this mid-day period is often the mildest time of day, which limits the value of reducing the ventilation rate, because temperature differences are small. During cooling, reducing the ventilation rate during the day is valuable, particularly in the mid- to late-afternoon. Consistent with this, Less & Walker (2017) found that hot climates had higher energy savings in the 1st shift compared with a 3rd shift occupancy pattern. Whereas this pattern was reversed in all of the heating dominated locations, where the 3rd shift had much higher energy savings. In general, an occupancy controller with a 1st shift schedule will operate opposite of a temperature-based controller. A temperature-based controller will over-vent during the day, when occupants are not present, and it will reduce the ventilation rate at night when occupants are home. These interactions will be addressed in our multi-parameter control cases described in Section 3.4.

Pre-occupancy flush out

We will also test versions of the occupancy controller where the controller can predict when occupants will return home. In these example cases, the controller begins the over-ventilation recovery period before occupants return home. We have reproduced a figure from Less & Walker (2017) demonstrating typical relative exposure patterns in an occupancy controller with no pre-venting, 1- and 2-hour pre-occupancy flush outs in Figure 10. This shows how the flush outs drastically reduce peak exposure to the occupants and lessen the over-ventilation period. For example, in the 9-hour absence pattern, the occupants return home at 17:00, and this controller would turn the fan on continuously starting at 15:00 for a 2-hour flush out. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. Less & Walker found that 1- and 2-hour flush outs had very similar energy performance, so we only test a 1-hour flush out in this work.

Less & Walker (2017) demonstrated that a pre-occupancy flush out paired with a RIVEC occupancy controller substantially increased energy performance of the controller, roughly doubling median energy savings for a 1st shift occupancy controller. They found similar savings when using a 1- or 2-hour flush out period. The reason the flush out was so effective was that it drastically reduced the peak relative exposure experienced by the occupants, as well as drastically reducing the over-ventilation requirements. This reduced the overall total air exchange required to maintain equivalence with the continuous fan. They reported that for a control with no recovery period, 60% of the over-ventilation requirement was due to controlling relDose to one, even after relExp was already below one. As noted earlier, greater reductions in air exchange lead to greater energy savings. Less & Walker found that just turning the fan off for 9-hours and not controlling exposure, reduced the air exchange rate by 38%. Using no pre-occupancy flush out reduced this to only a 12% reduction (26% was need to recover and maintain equivalence). In comparison, the 1- and 2-hour pre-occupancy flush outs had 22 and 28% reductions in AER.

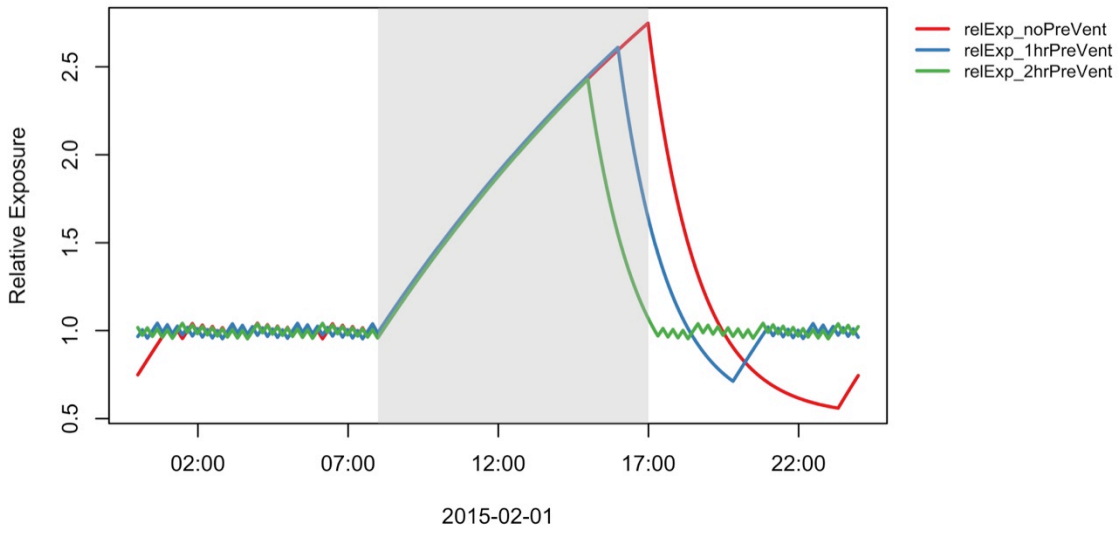

Figure 92 Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey. Reproduced from Less & Walker (2017).

The risk with the pre-occupancy flush out strategy is that it may be more difficult for a controller to predict when occupants will return home than it is to sense that they have returned home. The prediction requires a predictable pattern, whereas the simple approach with no flushing period requires only an accurate sensor (the low airflow during unoccupied times might also be more flexible in response to variable occupancy patterns). In addition, this only works for typical workweek schedules, with predictable home and away periods. Luckily, Less & Walker (2017) showed that a one-hour flush out was roughly equivalent in energy performance as the two-hour flush out, which gives the controller flexibility. A simple approach to predicting when occupants will return would be a running average of the prior five work day return times or the like. The system could also work on a schedule that is manually entered by the occupants that reflects their typical home and away patterns. Alternatively, a system could be used that is integrated with an occupant's cell phone that informs the controller when the occupants are within a certain radius of their home or some such approach.

An optimized pre-occupancy flush out would bring the relative exposure value to exactly one the minute occupants returned home. The two-hour pre-occupancy flush out happened to achieve this almost exactly in the test homes. In reality, this would vary with fan over-sizing, house size, natural infiltration, unoccupied time period, etc., and it would be nearly impossible to predict given variability in occupancy patterns. But the results reported by Less & walker (2017) suggest that this optimization might have little value, since 1-hour was nearly as good as 2-hour flush out. So, product designers do not need to worry about perfect prediction of occupancy patterns, rather being within an hour is sufficient.

Appendix H Auxiliary Fan Controls

A smart control strategy developed in the earliest versions of the RIVEC smart ventilation controller was to sense and detect operation of other exhaust devices in the home, including bathroom, kitchen and laundry fans, as well as a vented clothes dryer. The Auxiliary Fan SVC is a real-time RIVEC control that senses the operation of these other exhaust devices. These airflows are included in the estimate of the real-time ventilation (Q_i) and in calculation of relative exposure and dose as described in Section 2 (see Table 25 for control description). Essentially, these additional airflows are added to the ventilation rate used in calculating relative exposure and dose, so the central fan's operation can be traded off on a one-to-one basis with auxiliary fans. Total auxiliary fan operation was 160 minutes per day in each simulation, but the fan sizes varied between kitchen, bathroom and dryer fans. Roughly speaking, this allows the RIVEC fan to be turned off for approximately 160 minutes each day. This is distinct from controls that time-shift ventilation (i.e., temperature-based controls), because they have to increase the average ventilation rate in order to maintain exposure less than one, whereas this control reduces the average ventilation rate. The benefits of this type of control scale directly with the amount of auxiliary fan use and airflow. Secondary impacts depend on the time of day and outside temperature during auxiliary fan use.

Control Variable	***Fan ON Conditions***
Relative Exposure	>1
Relative Dose	>1

Table 25 Control details for Auxiliary Fan SVC.

Appendix I Detailed Description of the EMS Programs and Actuators

For each of the unique simulation scenarios the EMS control logic is contained in two different files. One file contains programs common to all scenarios (EMS_FMU_NoLeakage_WithFan_AllPath.imf), and one file (CONTROLS_[*control name*].imf) containing programs used only for the specific smart control and supporting objects used by that control. Table 26 lists all programs and the order they are called in. Table 27 lists the main EMS actuators used to implement smart ventilation control strategies and to capture the electrical energy use of the fans.

Table 26 EnergyPlus EMS Programs and call order

EnergyPlus EMS Programs	Function	Call sequence
Infiltation_Mixing	This is the main program used to collate the mass flow rates reported for each flow element in CONTAM, and to calculate the resulting mass and airflow in the attic and house zones.	1
CheckControlInputs	Sets and verifies the control specific parameters	2
CalculateControlDecision	Calculates the whole house flow rate (*WHFlow*) for each of the simulated control strategies, BaseFan, Occ, Cutoff, lockout, VarQ, VarRe and MedRe. For all controls, except VarQ, ControlDecision turns the main IAQ fan either on or off, based on the current and target relative exposure (and in some cases relative dose). VarQ calculates a continuously variable airflow value, rather than simply providing an on-off signal.	3
CalculateFanPowerUse	Calculates electrical power use by the IAQ fan based on the fan airflow, which is controlled by the ControlDecision smart controls. .Power use varies based on the scaled maximum power use (FanPowerRef), and the control flow ratio (FanRatio) that varies between 0-1 based on the fan control, such that: *WholeHouseFanPower=FanRatio*FanPowerRef* Where FanRatio is equal to the whole house flow rate (*WHFlow*) divided by the fan size (FanSize): *FanRatio= WHFlow / FanSize* Where the FanSize is taken directly from the scenario definition file (labeled FSM, in Table 34 below) and WHFlow is calculated in the CalculateControlDecision program. The FanPowerRef is the sum of the FanSize and the reference fan power (Fanpower), which is again a scenario input variable (IAQfanPower). *FanPowerRef = Fanpower*Fansize*	4
CalculateAirFlow	Estimates the whole house flow rates used by the smart controller, including infiltration, the IAQ fan, and when required by the control strategy, the auxiliary mechanical flows. Estimation is done as follows: 1. Estimate natural infiltration (Qinf), based on either the time-varying AIM-2 model or using the fixed annual effective infiltration rate from ASHRAE 62.2-2016	5

	2. If required, calculate any auxiliary fan airflows (AuxFans) including exhaust flows from the dryer, kitchen, and bathroom fans. 3. Specifically for the VarQ strategy, if the scenario specifies that the control takes the operation of the auxiliary fans into account when calculating the WHFlow, then adjust the WHFlow by the AuxFans flow rate accordingly. 4. Calculate the combined whole house airflow estimate (see Section 2) using different approaches for balanced verses unbalanced IAQ fans, using these equations based on ASHRAE 62.2 2016 Normative Appendix C, Section C2.3 Combination of Infiltration and Mechanical Ventilation. Equations C8-C9. For balanced IAQ fans and unbalanced auxiliary airflows: *TotalQ_m3s=Qinf*(Qinf/(Qinf+ AuxFans))+ WHFlow + AuxFans* For unbalanced IAQ and auxiliary airflows:: *TotalQ_m3s =Qinf*(Qinf/(Qinf+WHFlow+AuxFans))+ WHFlow + AuxFans,*	
CalculateExposureDose	Calculate the current "controller" relative exposure and dose based on the total ventilation airflow estimated in the AirFlow procedure described above	6
CalculateRealExposureDose	Calculates the "real" exposure/dose, based on the total ventilation airflow predicted using the co-simulation model, representing the actual ventilation in the model.	7
HVAC_Supervision	Temperature setpoint dead-band control , implements an effective lag in the operation of the heating and cooling system. For the heating operation, when the temperature of the zone is falling the heating system does not activate until it falls below an offset (set to 1degree C) below the set point. Heating is then turned off after the zone temperature rises more than the offset above the setpoint temperature. The actual thermostat uses a constant setpoint of 23 degrees C for both cooling and heating. The operation of the HVAC is then overridden by actuator control of the system availability, calculated based on the actual desired setpoint temperature and dead-band. The system is available for operation when the temperature of the zone is within the dead-band. This mimics the behavior of a residential HVAC system that would typically operate at full capacity and cycle depending on the thermal response of the space.	8

Table 27 EnergyPlus EMS Actuators

EnergyPlus EMS Actuators	Function
SupplyFanAvailability	Sets the HVAC fan availability schedule, used by the HVAC_Supervision program to control operation of the supply fan modeled in EnergyPlus. This allows the energy use of the supply air fan to be captured using the realistic fan performance curves defined in EnergyPlus for HVAC equipment.
Cooling_Availability & Heating_Availability	As above used for temperature setpoint deadband control in the HVAC_Supervision program defined below. Sets the availability schedule for the Coil:Cooling:DX and Coil:Heating:Gas objects respectively.
WholeHouseFanPowerOverride	Controls an EnergyPlus electrical equipment object used to track the whole house fan power use (WHFanPower). Power use is based proportionally to the fan flow rate, such that: WHFanPower= FanRatio*FanPowerRef Where FanRatio = *WHFlow* /FanSize FanPowerRef *WHFlow* whole house flow rate, and FanSize is the fan scaling factor read from the scenario definition file.
Living Infiltration_1 and UAtcInfiltration	Actuates the *Air Exchange Flow Rate* of the ZoneInfiltration:EffectiveLeakageArea objects used to set the total outdoor air infiltration for the living and attic zones. We confirmed that the rate set is a mass flow rate in units of kg/s.
LivingZoneToAHZoneMixing and AHZoneToLivingZoneMixing	Actuates the *Air Exchange Flow Rate (kg/s)* of two ZoneMixing objects, that represent the flow from the attic to the living zone, and from living zone to attic.
ExhuastFlow	Represents the total exhaust fan flow (IAQ fan, bathroom and kitchen). Sets a schedule value that is communicated to CONTAM via the FMI.
BalanceFlow	For scenarios with an air tightness of 1 ACH_{50}, the ExhuastFlow rate is balanced by an equivalent supply flow which is also sent to the CONTAM model,

Appendix J Infiltration Models Used in Smart Controls—Qinf and AIM-2

Consistent with the ASHRAE 62.2-2016 standard, natural infiltration is treated in one of two ways for our real-time relative exposure and relative dose calculations. Each smart control is tested with both methods of accounting for infiltration.

First, a fixed annual effective infiltration rate can be used, referred to as Q_{inf} and calculated as in Equation 7. These values are calculated according to house geometry, leakage area and location (wsf factors). This is the infiltration rate that would give the same annual relative exposure as the predicted time-varying infiltration rate, which is dependent on indoor and outdoor temperatures, as well as wind speed, direction and a host of other parameters. This effective infiltration value tends to under-predict infiltration rates when temperature differences are large or when it is windy, and it over-predicts infiltration when conditions are calm and with small temperature differences. The derivation of the current wsf factors is described in detail by Turner, Sherman, & Walker (2012).

The second approach to treating infiltration in demonstrating ASHRAE 62.2-2016 compliance is to use the AIM-2 infiltration model from the ASHRAE Handbook of Fundamentals, which provides real-time estimates of infiltration rates based on outdoor temperature and wind conditions. The 62.2 standard refers to this as the *Smaller Time Step Method* (Section C2.2.2). The model has been validated through field measurements (I. S. Walker & Wilson, 1998). The model inputs include house leakage area, shelter factors, wind speed modifiers, wind and stack coefficients.

The value of using AIM-2 in temperature-based smart ventilation controls is that it allows the controller to account for the fact that higher ventilation rates are in-fact occurring during times with greater temperature differences or wind. By accounting for this, the controller will reduce IAQ fan airflow rates, which should save energy. The controller will also know when natural infiltration rates are low, and it will compensate with higher IAQ fan airflows, but with less energy impact.

In order for a smart controller to apply the AIM-2 model, it would need reliable, real-time outdoor temperature and wind data. This is not always possible, and smart controllers can be effective without this data. So, for each of the most promising control strategies we test, we will assess their performance using Q_{inf} and using AIM-2 infiltration methods.

At each time-step (5-minutes in EnergyPlus), a natural infiltration estimate is calculated as the combined wind and stack airflows. Wind airflow (Q_w) is estimated using Equation 17. Stack airflow (Q_s) is calculated using Equation 18. The combined total airflow ($Q_{AIM\text{-}2}$) is estimated using Equation 19. The coefficients used in the model are selected based on house characteristics, including number of stories, foundation type, presence of a flue, etc. We used model coefficients assuming slab-on grade foundation and no flue present as outlined in Table 28.

$$\boldsymbol{Q_w = c \times C_w (sGU_{met})^{2n}} \quad \textbf{(17)}$$

$$Q_s = c \times C_s(|T_{in} - T_{out}|)^n \quad (18)$$

$$Q_{AIM-2,i} = \sqrt{Q_w{}^2 + Q_s{}^2} \quad (19)$$

$Q_{AIM-2,i}$ = total house infiltration at time step I predicted by AIM-2 model, L/s
Q_w = wind-induced infiltration airflow, L/s
Q_s = stack-induced infiltration airflow, L/s
c = house leakage coefficient, m^3/s-Pa^n
C_w = wind coefficient
s = shelter factor
G = wind speed multiplier
U_{met} = meteorological site wind speed, m/s
n = pressure exponent

Model Coefficient	***1-story***	***2-story***
Wind Speed Multiplier (G)	0.48	0.59
Shelter Factor (s)	0.5	0.5
Wind Coefficient (C_w)	0.156	0.170
Stack Coefficient (C_s)	0.054	0.078
Pressure Exponent	0.65	0.65

Table 28 AIM-2 model coefficients used in SVACH simulations.

Appendix K CONTAM Envelope Leakage Distribution, Wind Pressure Coefficients and Shelter Factors

Envelope Leakage Distribution

The leakage distribution refers to the orientation, height, size and locations of the leaks in a building envelope. The distribution of leaks, primarily by height, but also by orientation, can have substantial impacts on infiltration estimates. In addition to changing infiltration airflows, leakage distributions also affect how unbalanced fan airflow combines with natural infiltration to predict whole house airflow. The leakage distributions are described in detail for the 1- and 2-story prototypes in Table 29 and Table 30, respectively, including the height and size of each leak in the CONTAM models. In CONTAM, all leaks had discharge coefficients of 1.0 (a factor already accounted for in use of effective leakage area). The CONTAM envelope leakage flow elements are pictured in Figure 93. For the attic space, ceiling leakage was included, as were three cracks for each orientation representing unintentional attic leakage, as well as builder-installed venting to satisfy building code.

Floor height and wall leaks are evenly distributed on each of the cardinal faces of the homes, which is represented by the % values in the “Leakage Fraction, Total” vs. “Leakage Fraction, per Face” columns (the latter is simply the former value divided by 4). Five individual leaks are modeled on each of four walls, with heights evenly distributed along the total height of the walls (varies by number of stories). Overall, the 1-story homes have

25% floor height leakage, 25% wall leakage and 50% ceiling leakage (into the separately modeled attic zone), which is consistent with the default assumption of 50% ceiling leakage specified in the Title 24 2016 Alternative Calculation Method (ACM). The leakage areas in the 2-story homes have 16% floor height leakage, 52% wall leakage and 32% ceiling leakage. These values were selected to give leakage per unit wall/ceiling area roughly similar to those in the 1-story home, as well as similar leakage per linear foot of slab perimeter.

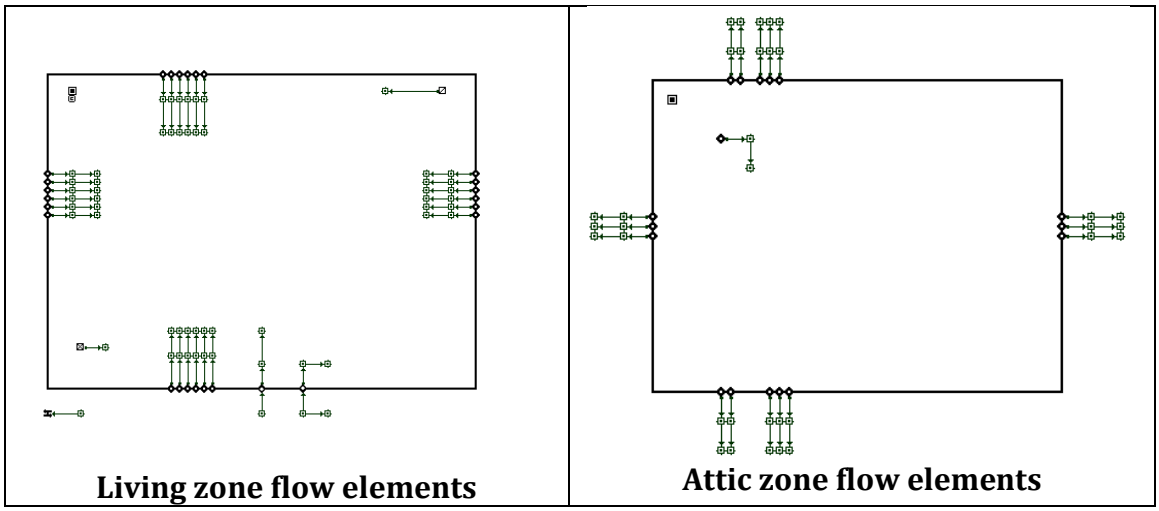

Figure 93 Location of flow elements on building envelope in CONTAM.

Leak Type	Leak Height From Floor (m)	Leakage Fraction, Total	Leakage Fraction, per Face	Leakage Areas Per Leak (cm^2)		
				1 ACH_{50}	3 ACH_{50}	5 ACH_{50}
Floor	0.0	25%	6.3%	6.64	19.91	33.18
Wall_1	0.3	5%	1.3%	1.33	3.98	6.64
Wall_2	0.8	5%	1.3%	1.33	3.98	6.64
Wall_3	1.4	5%	1.3%	1.33	3.98	6.64
Wall_4	1.9	5%	1.3%	1.33	3.98	6.64
Wall_5	2.5	5%	1.3%	1.33	3.98	6.64
Ceiling	2.7	50%	50.0%	53.09	159.28	265.47
Total		***100%***	***100%***	***106.19***	***318.56***	***530.94***

Table 29 1-story prototype house leakage distribution.

Leak Type	Leak Height From Floor (m)	Leakage Fraction, Total	Leakage Fraction, per Face	Leakage Areas Per Leak (cm^2)		
				1 ACH_{50}	3 ACH_{50}	5 ACH_{50}
Floor	0.0	16%	4.0%	5.79	17.36	28.93
Wall_1	0.6	10%	2.6%	3.76	11.28	18.81
Wall_2	1.7	10%	2.6%	3.76	11.28	18.81
Wall_3	2.9	10%	2.6%	3.76	11.28	18.81

Wall_4	4.1	10%	2.6%	3.76	11.28	18.81
Wall_5	5.2	10%	2.6%	3.76	11.28	18.81
Ceiling	5.8	32%	32.0%	46.30	138.89	231.48
Total		***100%***	***100%***	***144.67***	***434.02***	***723.37***

Table 30 2-story prototype house leakage distribution.

We customized the 2-story prototype's leakage area distribution, because the fixed 50% ceiling leakage assumption of Title 24 does not stand up to scrutiny when comparing the results for 1- and 2-story homes. For a 5 ACH_{50} home, the 1-story prototype (2100 ft^2) has total leakage area of 530 cm^2, or 265 cm^2 in the ceiling. The same 2-story prototype (2700 ft^2) has 722 cm^2 total leakage area, which would imply 361 cm^2 in the ceiling. This would create almost 100 cm^2 more leakage area in the ceiling, while the ceiling area in the 2-story home is roughly half that in the 1-story. Thus this fixed approach puts a lot more leakage area in a lot less ceiling area, effectively doubling the leakage area per unit ceiling area. We cannot think of a credible reason that 2-story homes would have double the leakage area per unit ceiling area. We hypothesize that the measurements by Proctor et al. represent an average distribution including both 1- and 2-story homes in the ECO study. Unfortunately, the average distribution may substantially misrepresent both home types—underestimating ceiling leakage fraction in 1-story homes and over-estimating it in 2-story.

The number of flow elements in the CONTAM model was chosen based on the trade-off between simulation accuracy and model complexity. We wanted to represent flow variation with orientation to adequately capture wind-driven ventilation, as well as by height in order to estimate vertical stack-driven forces due to temperature difference and height. The distribution of the cracks was based on expert understanding of typical distribution of attic leaks in California homes.

In addition to the infiltration flow elements, we also added two flow elements on the south wall to represent the whole house fan. For the balanced fan models, both flow elements are used to provide flow in opposite directions. In the unbalanced model a single flow element is used to represent an exhaust fan. No ducts were modeled in CONTAM, as they were considered to be in conditioned space, and therefore as having no effect on house air exchange with outside. The flow rate of the whole house fan is set by the smart ventilation controller.

Wind Pressure Coefficients and Shelter Factors

Envelope leaks are exposed to different pressures depending on their orientation and the direction of the wind. As such, CONTAM allows the user to apply either built-in or customized wind pressure coefficients, which vary by orientation. But CONTAM does not allow for use of shelter factors, which account for the effects of other nearby buildings on the wind pressures exerted on a building. Specifically, an isolated building experiences very different wind pressures than a home located in a row of other homes (as in the common block configuration in the U.S.). The exception in COINTAM is a global wind speed modifier

coefficient, which does not vary by wind direction, and therefore was not suitable for use in these building models.

We applied custom wind pressure coefficients and shelter factors for floor and wall leaks based on their orientation as detailed in Table 31. The wind pressure coefficients and shelter factors are the same as those used in the validated REGCAP heat, moisture and mass simulation model (I.S. Walker, Forest, & Wilson, 2005).

Incident Wind Angle	Combined Wind Pressure and Shelter Coefficients – HOUSE			
	North (0°)	South (180°)	East (90°)	West (270°)
30	0.531	-0.219	0.005	-0.527
60	0.261	-0.066	0.085	-0.247
90	-0.104	-0.084	0.035	-0.115
120	-0.055	0.256	0.069	-0.226
150	-0.200	0.531	0.004	-0.527
180	-0.300	0.600	-0.637	-0.650
210	-0.219	0.531	-0.527	0.005
240	-0.066	0.261	-0.247	0.085
270	-0.084	-0.104	-0.115	0.035
300	0.256	-0.055	-0.226	0.069
330	0.531	-0.200	-0.527	0.004
360	0.600	-0.300	-0.650	-0.637

Table 31 House custom combined wind pressure and shelter coefficients, by incident wind angle and surface orientation.

Attic leakage elements also had custom wind pressure coefficients, matching those used in the validated attic model implemented in the REGCAP simulation. The attic leaks do not have any sheltering and are reproduced in Table 32.

Incident Wind Angle	Combined Wind Pressure and Shelter Coefficients – ATTIC			
	North (0°)	South (180°)	East (90°)	West (270°)
30	-0.350	-0.277	-0.156	-0.250
60	-0.250	-0.060	-0.059	-0.284
90	-0.104	-0.085	-0.023	-0.154
120	-0.051	-0.245	-0.048	-0.259
150	-0.253	-0.350	-0.133	-0.250
180	-0.400	-0.400	-0.196	-0.200
210	-0.277	-0.350	-0.250	-0.156
240	-0.060	-0.250	-0.284	-0.059
270	-0.085	-0.104	-0.154	-0.023
300	-0.245	-0.051	-0.259	-0.048
330	-0.350	-0.253	-0.250	-0.133
360	-0.400	-0.400	-0.200	-0.196

Table 32 Attic custom wind pressure coefficients, by incident wind angle and surface orientation.

Appendix L EnergyPlus / CONTAM Co-Simulation Approach

Co-simulation setup

The co-simulation uses EnergyPlus as the master that communicates with a Functional Mockup Unit implementation of Contam. The FMU contains the Contam project model, a variable verification file (.vef) and a model description dictionary (.xml) and the Contam implementation (ContamFMU.dll). As introduced in Section 4.5, the *Contam 3D Export* tool from NIST is used to generate these files, and generate corresponding EnergyPlus EMS objects, as an .idf code snippet.

Setting up the co-simulation can be summarized in 3 steps. Firstly, the export tool may generate more data exchange elements than required, so step one is to remove unwanted variables from the .vef, .xml, and idf files. Step 2 is to check that all of the required variables are present in the files. Step 3 is to include the .idf snippet into the building model .idf and write the EMS scripts that will set and read values from the EMS *ExternalInterface* objects.

Section 1: Variable Declaration and Determining

The "modelDescription.xml" summarizes the parameter exchanging between EnergyPlus and CONTAM; Figure 102 shows an example snippet of the XML file.

```
<?xml version="1.0"?>
<fmiModelDescription fmiVersion="1.0" modelName="ContamFMU" modelIdentifier="ContamFMU"
guid="{818642F1-D7D4-4DC7-8549-554862454199}" variableNamingConvention="structured"
numberOfContinuousStates="0" numberOfEventIndicators="3">
  <ModelVariables>
    <ScalarVariable name="WTH_AmbientTemp" valueReference="1" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_BarometricPressure" valueReference="2" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_WindSpeed" valueReference="3" causality="input">
      <Real />
    </ScalarVariable>
    <ScalarVariable name="WTH_WindDirection" valueReference="4" causality="input">
      <Real />
```

Figure 94 FMU model description dictionary XML file

Data variables are sent from EnergyPlus to CONTAM, and from CONTAM to EnergyPlus, summarized in Table 33. There are a few predefined variables that are generated by the export tool that relate to the transfer of environmental data from EnergyPlus to Contam variable ID's 1-4. Summary variables, such as "MIX_2_attic_to_1_livingzone", do not need

additional specification. The remaining variables must be defined in the Contam model. Contam "control variables" are treated as inputs from EnergyPlus. Contam "reporting variables" are treated as data to be transferred to EnergyPlus. Figure 103 shows an example of adding a Split (or pass) input variable.

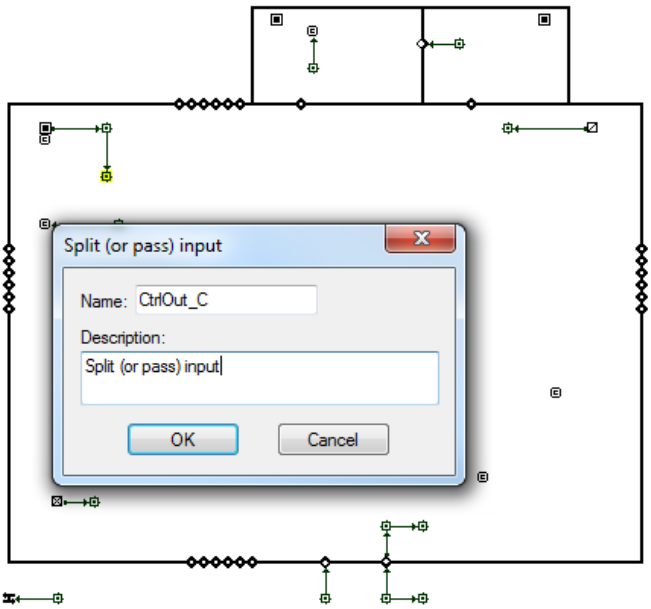

Figure 95 Control variable defined in CONTAM

The nomenclature for these variables, and for the variables described in the contam.vef file, can be found in the CONTAM user manual (Dols, Emmerich, & Polidoro, 2016), Section 6.2 ENERGYPLUS INPUT FILES.

Table 33 Variable exchanging dictionary summary

Default variables (from EnergyPlus to Contam)		
ID	Variable name	Description
1	WTH_AmbientTemp	Outdoor Dry-Bulb Air temperature, C
2	WTH_BarometricPressure	Outdoor atmospheric pressure, pa
3	WTH_WindSpeed	Wind speed, m/s
4	WTH_WindDirection	Wind direction
Control variables (from EnergyPlus to Contam)		
ID	Variable name	Description
5	TAIR_1_attic	Attic temp, C
6	TAIR_1_livingzone	Living zone dry-bulb air temperature, C

7	CTRL_I_CtrlIn_01	Air cleaning sink ratio
8	CTRL_I_CtrlIn_02	Outdoor air fraction
9	CTRL_I_CtrlIn_03	Total exhaust flow rate, m3/s
10	AHS_supply_1_livingzone	Supply air mass flow rate, kg/s
11	AHS_return_1_livingzone	return air mass flow rate, kg/s
12	PCTOA_SingleZoneAHU	OA fraction, %
13	TAIR_SingleZoneAHU(Rec)	Supply air duct temp,C
14	TAIR_SingleZoneAHU(Sup)	Return air duct temp,C
Reporting variables (from Contam to EnergyPlus)		
ID	Variable name	Description
15	MIX_2_attic_to_1_livingzone	Mass flow from Attic to living zone (air mixing), kg/s
16	MIX_1_livingzone_to_2_attic	Mass flow from living zone to attic (air mixing), m3/s
17	INFIL_1_livingzone	living zone infiltration from outside, m3/s
18	INFIL_2_attic	Attic infiltration from outside, m3/s
19	CTRL_O_CtrlOut_C	Living zone CO2 concentration
20	CTRL_O_CtrlOut_exhuast	Total exhaust mass flow rate, kg/s
21	CTRL_O_CtrlOut_mixing	Net Zone mixing from Attic to living zone, kg/s
22-	CTRL_O_CtrlOut_NW/WW/EW/SW_1/2/3/4/5	Air flow rate through envelop cracks, kg/s

The control variables are used to transfer data from EnergyPlus to CONTAM through the FMU, and are limited to values between 0 – 1, so we need to scale the value and match the units. Reporting variables, such as CTRL_O_CtrlOut_exhuast, can be floating point numbers.

The contam.vef variable exchange file is "used by the ContamFMU.dll to coordinate data exchange information at the beginning of a co-simulation run. This file will contain a list of variables that are to be exchanged during co-simulation." Figure 96 gives an example of a variable verification file used in this project. The first line is the total number of exchange variables, followed by the default and control inputs denoted by the string "I", and finally the reported outputs denoted "O". The second string, such as: "WTH_AmbientTemp" is the variable name, which must match the "modelDescription.xml" file. The three letter identifier, (wws, wvd etc) describes the type of data being transferred and is needed by CONTAM so that it knows which type of Contam data the variable connects to. The final string is the variable name as it appears in Contam. A more detailed description of these is found in the Contam user manual. (Dols, Emmerich, & Polidoro, 2016).

```
VariableExchangeFile 1.0 fmi 3
61
I WTH_AmbientTemp wat
I WTH_BarometricPressure wbp
I WTH_WindSpeed wws
I WTH_WindDirection wwd
I TAIR_2_attic zti  2 attic
I TAIR_1_livingzone zti  1 livingzone
I CTRL_I_CtrlIn_02 cti CtrlIn_02
I CTRL_I_CtrlIn_07 cti CtrlIn_07
I CTRL_I_CtrlIn_03 cti CtrlIn_03
I AHS_supply_1_livingzone ahs 1 livingzone 1
I AHS_return_1_livingzone ahr 1 livingzone 1
I PCTOA_SingleZoneAHU poa SingleZoneAHU
I TAIR_1_SingleZoneAHU(Rec) zti 1 SingleZoneAHU(Rec)
I TAIR_1_SingleZoneAHU(Sup) zti 1 SingleZoneAHU(Sup)
O MIX_1_livingzone_2_attic mix 1 livingzone 2 attic
O INFIL_2_attic inf 2 attic
O MIX_2_attic_1_livingzone mix 2 attic 1 livingzone
O INFIL_1_livingzone inf 1 livingzone
O CTRL_O_CtrlOut_mixing cto CtrlOut_mixing
```

Figure 96 Variable verification file

Variable Matching

All variables defined in the must be present in the the .vef, .xml, must also have a corresponding EMS interface object associated with it in the model .idf file. The variables transferred from EnergyPlus need an ***ExternalInterface:FunctionalMockupUnitImport:From:Variable*** object , and all the variables transferred into EnergyPlus require a ***ExternalInterface:FunctionalMockupUnitImport:To:Variable*** object. Furthermore, the variables transferred from EnergyPlus are also required to be specified in "Output:Variable". The variables from EnergyPlus can either be a variable calculated in core EnergyPlus programs or defined in EMS. Variables defined in EMS are needed to be defined as global variables.

Confirming Moist-Air Conditions and Mass Flow Rates Between EnergyPlus and CONTAM

For the co-simulation results to be meaningful, it is essential that the two tools represent the same thermodynamic conditions, and that the infiltration rates calculated in CONTAM are faithfully replicated in EnergyPlus. This is complicated by the fact that the current version of the contamFMU does not specify the humidity of the air. This presents a problem

when trying to harmonize our two models. When CONTAM is used as a standalone application (not using co-simulation), its moisture and mass balance model considers the humidity of the indoor and outdoor air in its calculation, with the outdoor humidity coming from a weather file. When using co-simulation however, the weather data, outdoor temperature, wind speed and direction, come from EnergyPlus's weather file via the FMI. CONTAM's moisture balance calculation then assumes dry air for its calculations, resulting in different assumptions of air density in the two tools. This presents an issue if the method described by Dols et al (Dols & Polidoro, 2015) is employed. Dols et al. pass the air change rate from CONTAM to EnergyPlus as a volumetric air change rate that is calculated by CONTAM using the dry air density. When we initially implemented the off-the-shelf contamFMU, we found mass imbalances between the two tools, which led to a reported loss of mass. This discrepancy was deemed unacceptable and so we abandoned the approach of having CONTAM calculate the zone infiltration, and instead used an EnergyPlus EMS program to calculate the total zone infiltration. In this approach, the mass flow rate of every flow path in the CONTAM model was sent to EnergyPlus, and net-ventilation airflows were calculated for the main zone and attic using a calculation in EMS code. This customization ensured that mass was maintained and balanced between CONTAM and EnergyPlus.

The equation used in EMS code for this calculation is:

$$\dot{\boldsymbol{V}}_{\boldsymbol{oa}} = \frac{\sum \boldsymbol{m}_{\boldsymbol{inf}} + \sum \boldsymbol{m}_{\boldsymbol{mix}}}{\boldsymbol{\rho}_{\boldsymbol{zn}}} \tag{20}$$

where $\dot{V}_{oa}$ is the volumetric flow rate for fresh air coming into the zone, $\sum \dot{m}_{inf}$ is the sum of the infiltration mass flow rates into the zone through all the cracks, $\sum \dot{m}_{mix}$ is the sum of the zone mixing mass flow rates into the zone from the Attic, and ρ_{zn} is the zone air density (as a function of house zone temperature, humidity and atmospheric pressure).

The mass flows into the conditioned house zone were converted to a volumetric ventilation airflow using EnergyPlus's moist air density. This volumetric airflow was then used to specify the volumetric air change rate in EnergyPlus using a *DesignInfiltration* object. EnergyPlus reports this air change rate as a mass flow rate, which was confirmed to be the same as the mass flow rate returned from CONTAM.

Appendix M Detailed Scenario File Description

Table 34 describes all of the input parameters in the scenario input file, and their uses.

Table 34 Scenario definition file

Parameter	Example	Description/purpose
ID	85	Numerical id allocated sequentially
KeyTerm	1story_1ACH50_CZ10	Unique prototype identifier, including all combinations of the 24 prototype homes (3 airtightness levels, 4 climate zones and 2 prototype home geometries)
Prototype	1story	Selects EnergyPlus building model geometry for 1- or 2-story
cz	X10	Selects CEC climate zone (1, 3, 10 or 16)
czID	10	ID for climate zone
ACH50	1	Building envelope air tightness (ACH50)
AIM_C	0.011135023	Envelope leakage coefficient, AIM-2 model . Parameter c used in controller infiltration calculation using AIM-2 method
AIM_Cs	0.054	Stack coefficient, AIM-2 model. Parameter cs in controller infiltration calculation using AIM-2 method
AIM_Cw	0.156	Wind coefficient, AIM-2 model. Parameter cw in controller infiltration calculation using AIM-2 method
AIM_G	0.48	Wind speed multiplier, AiM-2 model. Parameter G in controller infiltration calculation using AIM-2 method
AIM_s	0.5	Shelter factor, AIM-2 model (see Appendix J). Parameter s in controller infiltration calculation using AIM-2 method
Cmean	NA	Cooling season mean relative exposure target. Not used directly in simulations, but provides meta-information about the case.
ControlType	Occ	Control type for different control strategies
CoolingAHUfanPower_w	320	Cooling system air handler fan power consumption, watts
CoolingAirflow_m3.s	0.38	Cooling system air handler airflow rate (designed value), m3/s
EER	12.8	Cooling system EER (converted to COP)
ELA_m2	0.010618807	Effective leakage area, used in Contam model
FSM	2	Fan speed multiplier, used to increase airflow of baseline IAQ fan
Fan.Type	HRV	Specifies if the "Balanced" vs. "Exhaust"
Flush1	0	Occupancy control pre-occupancy flush out, hour 1
Flush2	0	Occupancy control pre-occupancy flush out, hour 2
Flush3	0	Occupancy control pre-occupancy flush out, hour 3
Flush4	0	Occupancy control pre-occupancy flush out, hour 4
HeatingAHUfanPower_w	161.3	Heating system fan rated power, watts
HeatingAirflow_m3.s	0.19	heating system air flow rate (designed value), m3/s
HeatingCapacity_J.s	7033.705684	Heating system capacity, J/s
Heating_AFUE	0.92	Heating system efficiency, Annual Fuel Utilization Efficiency
Hmean	NA	Heating season mean relative exposure target. Not used directly in simulations, but provides meta-information about the case.
IAQfanAirflow_m3.s	0.039911762	Continuous IAQ fan air flow from baseline case for each KeyTerm, m3/s. The Fan Size Multiplier is used to translate this into an over-sized fan for the smart control cases.
IAQfanPower_w	17.40551938	Continuous IAQ fan power from baseline case for each KeyTerm, watts
Infiltration	Qinf	Controller infiltration estimation method (AIM-2 or Qinf)
Qinf	0.003352683	Annual effective infiltration estimate from ASHRAE 62.2-2016,m3/s.
REMaxCooling	NA	High relative exposure target, used in VarRe, Cutoff and MedRe controllers.
REMaxHeating	NA	Low relative exposure target, used in VarRe, Cutoff and MedRe controllers.

REmax	NA	High relative exposure target used during heating season to reduce ventilation, used in Seasonal controller
REmin	NA	Low relative exposure target used during cooling season to increase ventilation, used in Seasonal controller.
SixtyTwoTwoFan	0.039911762	Continuous IAQ fan air flow from baseline case for each KeyTerm, m3/s. The Fan Size Multiplier is used to translate this into an over-sized fan for the smart control cases. Identical to IAQfanAirflow_m3s.
Strategy	NineHour	Occupancy schedule for "Occupancy" control
TCutoffCooling	78.8	Cooling cut off temperature for "Cut off" control, F
TCutoffHeating	57.4	Heating cut off temperature for "Cut off" control, F
Type		Not used
UnoccFlow	0.35	For Occupancy SVC, this is the fractional airflow relative to the baseline continuous IAQ fan airflow.
duration	9	Duration of unoccupied period.
proto	1	Not used
TmaxCoolingInF	NA	Cooling season maximum temperature used to proportionally scale control targets for the VarRe and VarQ controllers, F. For VarQ, this is the maximum cooling season temperature, and for VarRe this is some optimized value that is less than the maximum value.
TmaxHeatingInF	NA	Heating season minimum temperature used to proportionally scale control targets for the VarRe and VarQ controllers, F. For VarQ, this is the minimum heating season temperature, and for VarRe this is some optimized value that is greater than the minimum value.

Appendix N Weighted Average Method

In addition to reporting results across the house and simulation parameters described above, we also perform a weighted average assessment, which is targeted towards representing smart ventilation control performance in new homes built in California. As such, the weighted average method gives strong emphasis to the types of homes that are built in the state and where they are built. Namely, this means strong weighting for cases with more air leakage in climates 3 and 10 (Oakland and Riverside).

Each case is weighted according to the expected distribution of the parameter in new homes throughout the state. The weighted average parameters used in our analysis included climate zone (see Table 37 and Table 38), envelope airtightness (Table 35) and house prototype (Table 36). Each factor is briefly discussed below. This is an imperfect approach to characterizing the entire new California single-family building stock, but it does give us a way to generalize and summarize our results. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon). The average result under these weights for each fan sizing method was calculated using Equation 21.

$$\overline{x} = \frac{\sum_{i=1}^{n}(x_i * w_{prototype,i} * w_{cz,i} * w_{ACH50,i})}{\sum_{i=1}^{n} w_{prototype,i} * w_{cz,i} * w_{ACH50,i}} \quad \textbf{(21)}$$

x = Variable in question (e.g., relative exposure, ventilation energy use)
$w_{prototype}$ = house prototype weight
w_{cz} = climate zone weight
w_{ACH50} = airtightness weight

The airtightness weights (Table 35) are designed to roughly estimate current airtightness in new California homes, with most new construction achieving roughly 5 ACH_{50}, and diminishing numbers of new homes achieving 3 ACH_{50} and very low numbers with greater airtightness of 1 ACH_{50}.

	Envelope Airtightness (ACH_{50})		
	5	***3***	***1***
Estimated Weights	0.63	0.30	0.07

Table 35 Envelope airtightness weighting factors

Prototype weights (Table 36) match those provided in the description of the single-family Title 24 prototype buildings that are used for analysis supporting development of the Title 24 energy code (Nittler & Wilcox, 2006).

	1-story, 2,100 ft^2	***2-story, 2,700 ft^2***
Weighting Factor	0.45	0.55

Table 36 Prototype weighting factors

Climate zone weights (Table 37 and Table 38) are based on the fraction of total projected new housing starts in 2017 in each CEC climate zone, using data provided to the 2016 CASE teams by the CEC Demand Analysis office. We have reproduced exactly the estimates provided by Rasin & Farahmand (2015) in Table 14 of the Residential High Performance Walls CASE report. Yet, we simulated only climate zones 1, 3, 10 and 16, and we attribute projected housing starts in non-simulated climate zones based on geography and overall heating/cooling degree days (see Table 37 for our assignment of non-simulated climates to those we simulated, for example, the CZ4 and CZ5 weights were added to the CZ3 weighting). The combined weights for zones 1, 3, 10 and 16 are provided in Table 38. The vast majority of weight (96%) is applied to the CZ3 and 10 results.

CZ	***City***	***2017 New Single-Family Homes***	***2017 New Homes Fraction***	***Rough HDD_{65} Range***	***Rough CDD_{80} Range***	***CZ Weight Assignment***
1	Arcata	695	0.006	3800-4500	0-50	1
2	Santa Rosa	2602	0.024	2600-4200	200-900	3
3	Oakland	5217	0.048	2500-3800	10-500	3
4	San Jose-Reid	5992	0.055	2300-2900	200-1000	3
5	Santa Maria	1164	0.011	2300-3000	200-900	3
6	Torrance	4142	0.038	700-1900	500-1200	10
7	San Diego-Lindbergh	6527	0.060	1300-2000	500-1100	10
8	Fullerton	7110	0.066	1300-1800	700-1300	10
9	Burbank-Glendale	8259	0.076	1100-1700	1300-1600	10

10	Riverside	16620	0.154	1600-1900	1400-1900	10
11	Red Bluff	5970	0.055	2500-4300	600-1900	3
12	Sacramento	19465	0.180	2400-2800	900-1600	10
13	Fresno	13912	0.129	2000-2700	1000-2200	10
14	Palmdale	3338	0.031	1900-2700	2000-4200	10
15	Palm Spring-Intl	3885	0.036	1000-1300	4000-6600	10
16	Blue Canyon	3135	0.029	4300-6000	200-1000	16

Table 37 New construction estimates for single-family homes in 2017 and weighting assignments for un-simulated climate zones.

	1 (Arcata)	***3 (Oakland)***	***10 (Riverside)***	***16 (Blue Canyon)***
Total Weight Factor	0.0064	0.1939	0.7707	0.0290

Table 38 Climate zone weighting factors.

Appendix O Normalization Method

Due to both smart control and baseline cases having controller relative exposure not exactly equal to 1.0 (as initially discussed in Section 5), normalization was performed as follows.

We created a set of cases for each combination of climate zone and house prototype (two prototypes, four climates) that had no air exchange either through fans or natural infiltration. Energy consumption in these cases was deemed the "envelope-only" energy use. This envelope energy use was subtracted from the HVAC energy use for each standard case to estimate the total energy consumption added to the home by outside air exchange (including both mechanical and natural airflows). This ventilation energy was then multiplied by the annual mean controller exposure for the case, in order to estimate the ventilation energy use that would have occurred if the controller exposure was exactly 1.0. For example, if a case was slightly over-ventilated relative to the target airflow (e.g., mean exposure of 0.98), the ventilation energy use in that case was multiplied by 0.98 to approximate the slightly lower ventilation energy use that would have occurred if exposure were equal to 1.0. This normalized ventilation energy was then added back onto the envelope-only energy use for each case, and these adjusted HVAC energy use values were used to estimate energy savings of smart controls relative to baseline continuous IAQ fan cases.

We also tested an alternative normalization approach that parametrically varied the smart control parameters in order to get controller exposure to equal 1.0, and the two normalization methods had very good agreement in predicted total HVAC energy use. So, in this work, we present the results of the simpler method described in the prior paragraph.

Appendix P Demand Response and Peak Demand

California faces unique grid reliability issues due to its high saturation of renewable energy sources (e.g., solar, wind and hydro), as well as issues with servicing the peak electricity demand on the hottest days of the year. Accordingly, the utilities offer time-of-use rate plans, in accordance with CPUC requirements. Some also issue peak day alerts for 9-15 days per year, typically the hottest days, when customers are encouraged to shed electrical demand using a very high price signal, roughly $0.85 per kWh. These efforts are termed Demand Response, and the goal is to get utility customers to voluntarily reduce their energy demand at certain times of day and on certain days of the year.

Smart ventilation controllers can contribute to demand response peak demand savings, largely by reducing the ventilation portion of the cooling load during the hottest times of day. In fact, many of the smart ventilation controls that we tested in this work automatically perform peak shedding, due to their outdoor temperature controls, which will reduce the ventilation rate during hot (or cold) periods. In addition to this, some of the controls might offer additional peak period benefits through pre-cooling with increased ventilation rates at night, effectively acting like economizers. That being said, none of the controls assessed in this work are specifically "demand response" or "peak demand" controllers. Such a controller would do nothing but turn the IAQ fan completely off during the peak period(s). Some of the smart controls do something very similar to this, but in general, they are reducing the IAQ fan airflow during hot outdoor conditions, rather than fully turning it off.

We assess peak period performance by assessing the HVAC power consumption that is shed during the peak hours on the hottest days of the year in the smart control cases relative to the baseline cases. The peak period is assumed to be between 2 and 6pm (per PG&E rate plans) on the hottest 10-days of the year—a total of 40-hours of the year. We select different sets of 10-days for each CEC climate zone weather file. We first calculate the average temperature between 2 and 6 pm for each day of the year. We then select the 10 warmest days on average as our "peak" days. Finally, we estimate total HVAC energy consumption during these peak periods, including the compressor, furnace, air handler, IAQ fan and auxiliary fan power consumptions. For demand response estimates, we estimate the reduction in average wattage during the 4-hour peak period, as well as percent reduction in the entire HVAC load during the peak period.

Appendix Q Time Dependent Valuation (TDV) Energy

In addition to the peak analysis described in Appendix P, we also calculate energy performance using time dependent valuation energy, as is required to demonstrate compliance with the Title 24 building energy code. TDV changes the value of energy depending on when it is used, with higher penalties for consumption during periods that stress the grid and increase consumer and grid operation costs. TDV factors are provided for every hour of the year for electricity and gas, and they vary by CEC climate zone. We use the TDV factors built into the compliance weather files provided by the CEC for use in the

CBECC-Res software. We combine these with the hourly energy consumption estimates from EnergyPlus for the cooling, heating, air handler and ventilation fan equipment. We generally report TDV savings in a percentage format, but we use kilowatt-hours when reporting absolute energy use. We convert TDV from Btus to kWh by dividing by 3,412. It is critical to note that the smart controls that were designed through parametric optimization (e.g., VarQ, VarRe, CutOff) were not optimized using TDV energy, but rather simple site energy savings. The same optimization could be performed based on TDV consumption, and surely the ideal control parameters would change and we expect TDV savings would increase accordingly.

Appendix R Mechanical IAQ Fan Sizing

Baseline Fan Sizing

All baseline ventilation fans are sized according to the current calculation method in ASHRAE 62.2-2016. This means a target ventilation rate (Q_{tot}) is calculated based on home floor area and number of occupants/bedrooms as in Equation 22. An effective annual average infiltration airflow (Q_{inf}) is then estimated using the results of a blower door pressurization test as in Equation 23. Finally, a mechanical fan airflow (Q_{fan}) is calculated using the target airflow and estimated infiltration per Equation 24.

$$\boldsymbol{Q_{total} = 0.15A_{floor} + 3.5(N_{br} + 1)} \quad \textbf{(22)}$$

Q_{total} = Total required ventilation rate, L/s
A_{floor} = floor area of residence, m^2
N_{br} = number of bedrooms (not less than one)

$$\boldsymbol{Q_{inf} = \frac{NL(wsf)A_{floor}}{1.44}} \quad \textbf{(23)}$$

Q_{inf} = Effective annual infiltration rate, L/s
NL = normalized leakage, derived from blower door testing
wsf = weather and shielding factor from Normative Appendix B 62.2-2016, varies by climate zone
A_{floor} = floor area of residence, m^2

$$\boldsymbol{Q_{fan} = Q_{total} - \emptyset(Q_{inf} \times A_{ext})} \quad \textbf{(24)}$$

Q_{fan} = required mechanical ventilation rate, L/s
Q_{total} = Total required ventilation rate, L/s
Q_{inf} = Effective annual infiltration rate, L/s
A_{ext} = 1 for single-family detached homes
ϕ = 1 for balanced ventilation systems and otherwise: Q_{inf}/Q_{tot}

Baseline Exposure and Superposition in ASHRAE 62.2

Our results showed the baseline continuous fan cases were under-ventilated relative to the targets established in ASHRAE 62.2-2016, yet the fans were sized using the standard. We found that relative exposure was greater than one in these cases, because of a bias in the methods used to combine unbalanced mechanical and natural infiltration airflows—referred to as superposition. This bias impacts fan sizing calculations and house airflow estimates when calculating relative exposure. The bias is problematic when designing and assessing smart controls, because the standard requires them to achieve exposure less than 1.0, while the baselines do not meet that same criteria. This acts as an energy disadvantage for the smart controlled fan. The energy penalty of increasing airflow can be similar in magnitude to the anticipated smart ventilation savings for some controllers (see Less and Walker (2017)). Balanced ventilation fans are not subject to the superposition equations in 62.2-2016, so do not suffer from this bias in fan sizing or house airflow estimation.

ASHRAE Standard 62.2-2016 sizes an IAQ fan using a target airflow (Q_{tot}) and an estimation of infiltration (Q_{inf}) that is based on a blower door test. Until recently, fans were sized in all cases by simply subtracting infiltration from the target airflow ($Q_{fan} = Q_{tot} - Q_{inf}$). Superposition equations were introduced in ASHRAE 62.2-2016 in order to account for the different ways in which balanced and unbalanced fans combine with natural infiltration. The old formulation used in the standard (i.e., simple addition of fan and infiltration airflows) ensured, almost by definition, that unbalanced IAQ fans did not achieve the target ventilation rate (Q_{tot}). Estimation of a number of new superposition models was presented by Hurel, Sherman, & Walker (2016). Each model could be formulated to either predict house airflow or to size a ventilation fan based on a target airflow. The most simple and accurate models were incorporated into ASHRAE 62.2-2016 for fan sizing calculations (by Addendum S), and for estimation of total house airflow when using relative exposure to demonstrate compliance (as is done with smart controls). But two discrete and different models were used for these two applications, and they are not an identity forwards and backwards. The result is that if you size a fan based on a target airflow and an infiltration estimate, and you then combine that resulting fan airflow with the same infiltration estimate, you do not get the target airflow back out of the systems of equations. Rather you always get an estimated airflow less than the target airflow.

Both superposition models incorporated by the standard calculate a phi sub-additivity coefficient, which is used to adjust the infiltration estimate when using unbalanced ventilation fans.

The "backward" formulation is used in fan sizing:

$$\emptyset_{backward} = \frac{Q_{inf}}{Q_{tot}} \tag{25}$$

$$Q_{fan} = Q_{tot} - \emptyset_{backward} \times Q_{inf} \tag{26}$$

The "forward" formulation is used in estimating total airflow:

$$\emptyset_{forward} = \frac{Q_{inf}}{Q_{inf}+Q_{fan}} \quad (27)$$

$$Q_{house} = Q_{fan} + \emptyset_{forward} \times Q_{inf} \quad (28)$$

For nearly any example set of values, Q_{house} (the result of forward estimation) is not equal to Q_{tot} (the target value used in fan sizing). For example, a target airflow of 50 L/s (Q_{tot}) and infiltration of 20 L/s (Q_{inf}) gives a fan size of 42 L/s (Qfan = 50 – 20 x (20 / 50)). But in the reverse formulation, Q_{house} is 48.5 L/s (42 + 20 x (20 / (20 + 42)). This will lead to a relative exposure of 50/48.5 = 1.03.

This imbalance in fan sizing and airflow estimation depends on the ratio of the infiltration (Q_{inf}) to the target airflow (Q_{tot}). We show resulting relative exposures (target airflow Q_{tot} divided by predicted house airflow Q_{pred}) for continuous unbalanced fans across a range of Q_{inf}/Q_{tot} ratios in Figure 97 below. The peak effect occurs when infiltration is 80% of the total airflow, with a relative exposure just below 1.1. There is nearly no effect when the infiltration is much smaller than the target airflow.

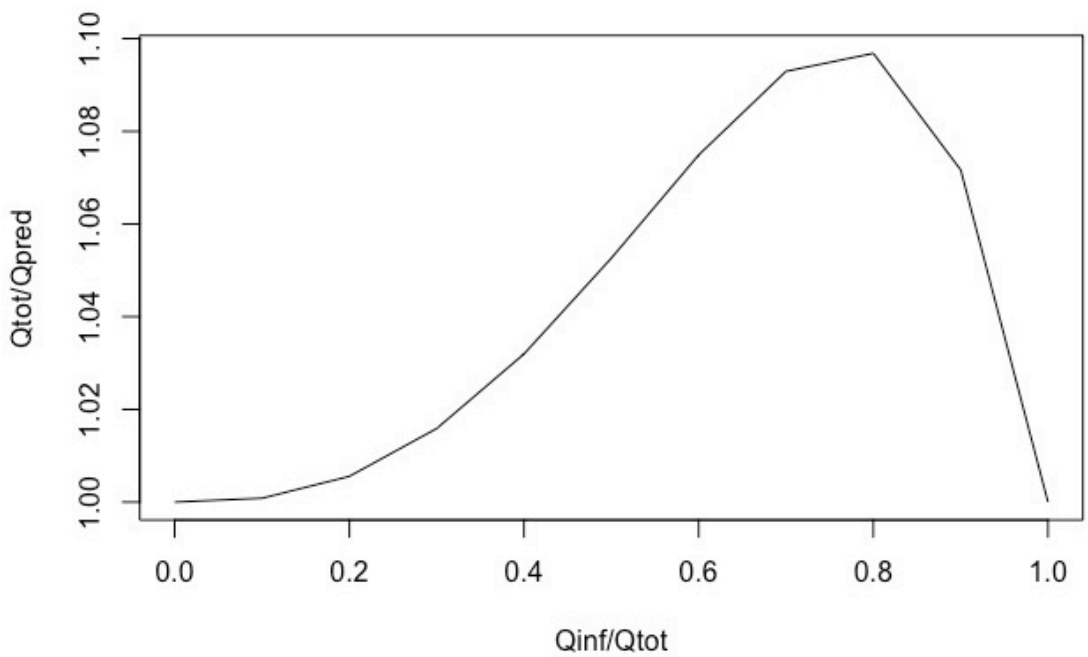

Figure 97 Illustration of bias in the ASHRAE 62.2-2016 unbalanced fan sizing calculation.

Smart Control Fan Sizing

To maintain equivalence with homes ventilated to the target airflow calculated using ASHARE 62.2-2016, smart controlled fans that time-shift ventilation rates must be over-sized. Most SVC fans are double the flow of the corresponding baseline cases. Where fans are not doubled, the Fan Size Multiplier (FSM) is noted in the control description. This

multiplier is sometimes also used directly in the control development and setting of control parameters. For example, the smallest exposure value that a fan can achieve is well approximated by 1/FSM. If the FSM is 2 (double the baseline), then the steady state concentration at full fan flow would be half that in the baseline case. A triple over-sized fan could reach a minimum exposure of 1/3, etc. The lower the exposure is able to go, the more under-ventilation the controller can use to strategically save energy. For example, the target high and low exposure values used in the running median control are FSM and 1/FSM, respectively.

This approach works very well in a very airtight home, where the fan airflow is nearly equal to the whole house airflow. But in the leakier homes, the ventilation fan is only a fraction of the target ventilation rate, so doubling the fan airflow fails to double the whole house airflow. In effect, fan airflow doubles, infiltration is unchanged, and the resulting whole house flow is slightly less than doubled, and exposure is greater than the 1/FSM target (e.g., 0.5). So, the minimum exposure target used in some control types may in fact not be reachable, which skews the exposure higher than desired. This issue worsens as the natural infiltration rate (Qinf) predicted using ASHRAE 62.2-2016 equations increases relative to the target ventilation rate (Qtotal). Many of the SVC are designed to achieve an annual exposure of 0.97 (instead of 1.0) to account for just such imperfections in control structure, definitions and operation.

We expect that the sizing of the smart controlled fan will have substantial impacts on performance, with effects varying strongly by the type of control strategy and eve fan type. Less & Walker (2017) showed that when using occupancy controls, increasing the size of a balanced IAQ fan had very little impact on energy performance, though the annual average exposure went down marginally as fan size increased. They also found that using an unbalanced fan with a controller that cycles the fan on and off led to increases in annual air exchange and associated ventilation energy. This was the result of superposition effects in the combining of unbalanced airflows with natural infiltration. To summarize, unbalanced fan airflows are sub-additive with natural infiltration (see Equation 24), and the amount of additional airflow provided by a fan changes with the ratio of the fan airflow to the infiltration airflow. As the fan airflow gets larger relative to the infiltration airflow, the fan contributes more to total house airflow—it gets more credit. As the fan gets smaller relative infiltration, it gets less credit. When a larger fan cycles on and off to provide the same relative exposure as a continuous fan with lower airflow, the unavoidable result is that the average air exchange increases for the cycling fan (as does ventilation energy use). This occurs for unbalanced smart controlled fans, but would also apply to any unbalanced ventilation system operated on a timer or otherwise cycled to maintain an average airflow.

For smart controls that do not change their target exposure values or overall control approach with fan size, we expect nearly no effect for balanced fans, and moderate negative effects for unbalanced fans as their over-sizing increases. But other smart control strategies, such as some of the temperature-based controls, change their target relative exposure values based on fan sizing. In these cases, larger smart controlled fans should

increase energy savings, because they allow more time shifting of ventilation than smaller fans do.

Appendix S Sensitivity Analysis

Airtightness

We estimated the median ventilation site and TDV energy savings for each control type across airtightness levels (see site energy in Figure 98 and TDV in Figure 99). Most new homes in the state are currently being built in the 4-5 ACH_{50} range, and we expect that as new homes become zero energy with the 2019 code cycle, homes at the 3 ACH_{50} level will increase to some extent. Homes at 1 ACH_{50} are rare and will remain so, so we consider this the least relevant data segment.

The controls respond differently to airtightness, with some having fairly consistent responses across airtightness levels (e.g., Seasonal control for site energy, or VarRe control for TDV), while most others vary. The 5 ACH_{50} performed the best for many control types when considering site energy, but this benefit disappeared for TDV assessments, where the leakiest homes were either similar to or worse than the most airtight cases (for top-performing VarRe, VarQ and Cutoff controls). VarQ site energy performance at the 5ACH_{50} leakage level does not perform as well as other controls. Most notably, the VarRe control performs similarly to VarQ in 3 ACH_{50} cases but substantially outperforms it in the leakiest homes, giving it the clear advantage on average. For TDV savings, the VarQ is much better than VarRe in all air leakage levels, but especially for the 3 ACH_{50} cases.

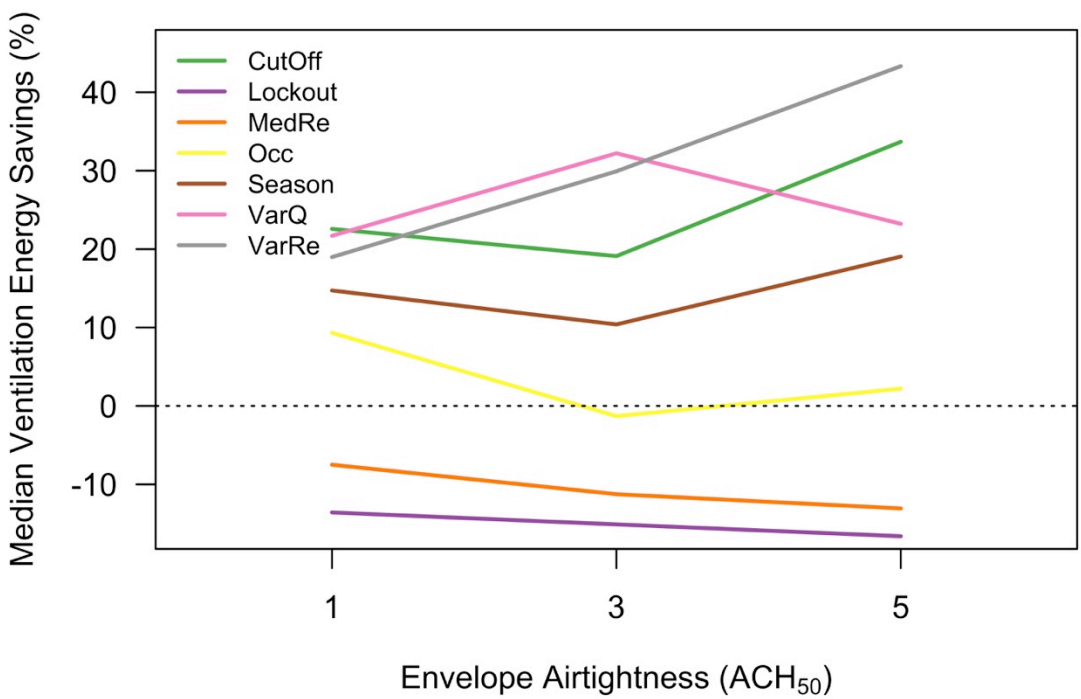

Figure 98 Median ventilation energy savings aggregated by airtightness and control type.

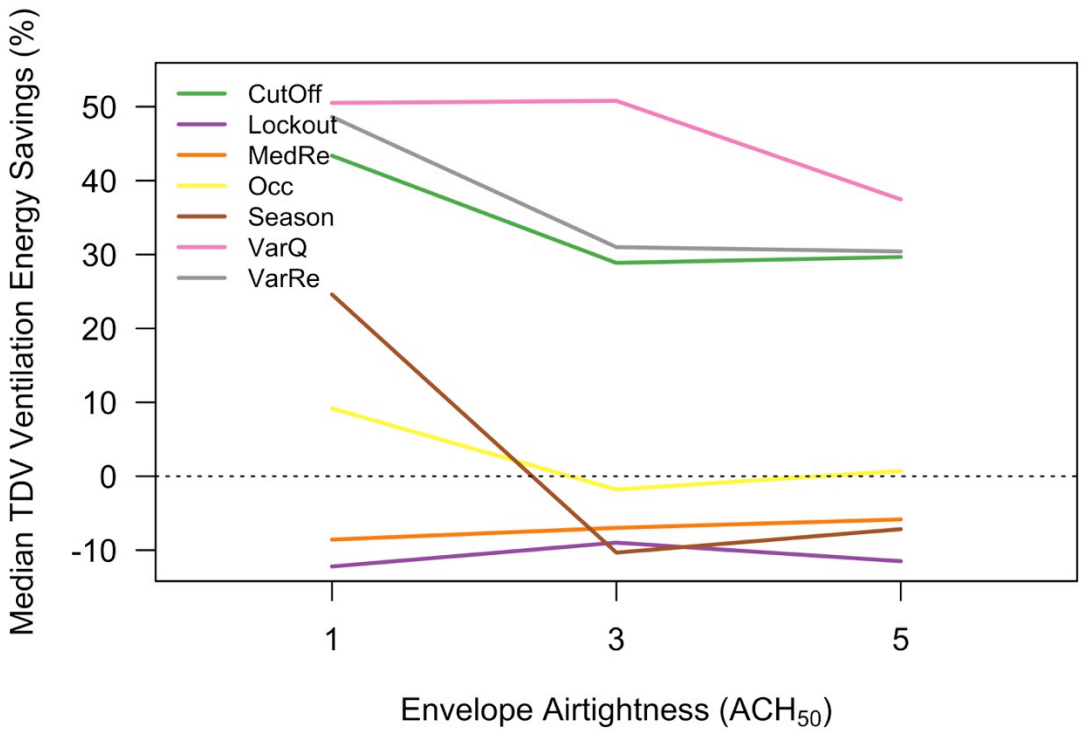

Figure 99 Median TDV ventilation energy savings aggregated by airtightness and control type.

Climate Zone

The SVC also varied a lot by climate zone, with CZ10 (Riverside) having the highest site energy ventilation savings for nearly all control types. CZ3 and 16 were generally similar in performance, while CZ1 had by far the lowest average savings across all control types. This relationship shifts when using TDV energy, with CZ3 (Oakland) generally having the greatest ventilation TDV energy savings across some control types (CutOff and VarRe), while others still had maximum savings in CZ10 (VarQ, Lockout and MedRe). Median TDV ventilation energy savings for VarQ were by far the greatest of all controls in CZ10 (median savings >60%), where most new home development occurs in the state. The next best control in terms of TDV savings had 20% lower median ventilation savings. The other CZ with large amounts of development is CZ3, and VarQ performs similarly in that location to the Cutoff and VarRe controllers.

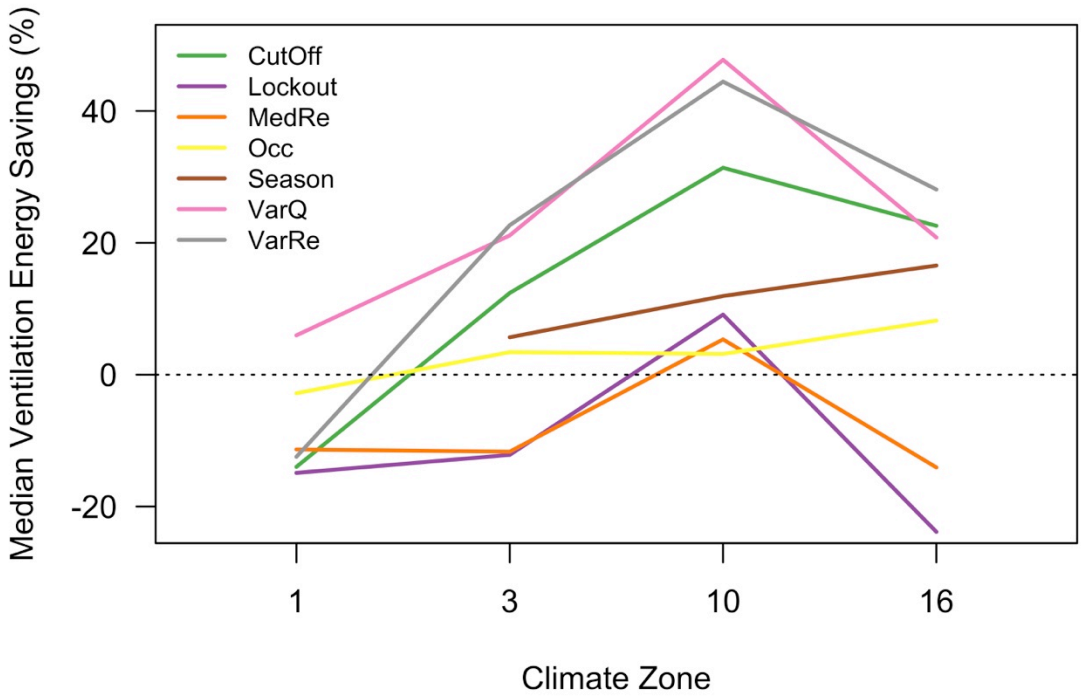

Figure 100 Median ventilation energy savings aggregated by climate zone and control type.

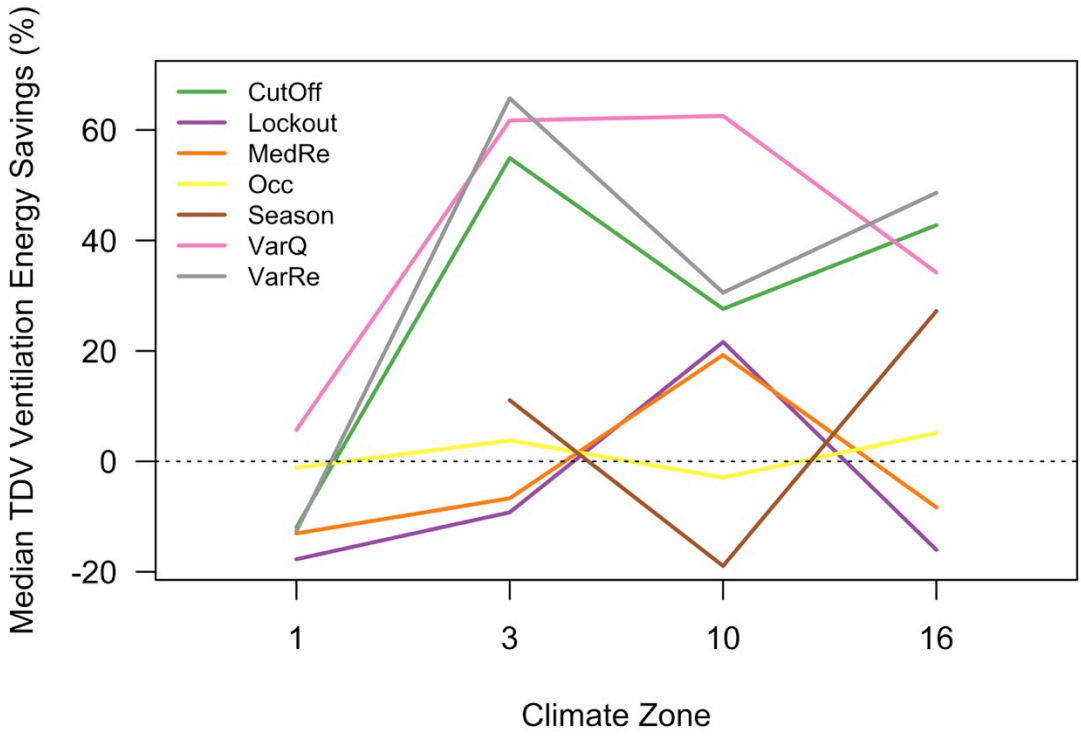

Figure 101 Median TDV ventilation energy savings aggregated by climate zone and control type. Prototype House

Prototype

Smart control performance also varied by the prototype house—2-story large (2,700 ft^2) vs. 1-story medium homes (2,100 ft^2). We show the median site ventilation savings for each control type and prototype home in Figure 102 (TDV savings in Figure 103). Both the VarQ and Lockout controllers have substantially greater median ventilation savings in the 1-story medium homes, which is true for both site and TDV energy. For site energy, all other controls have marginally improved performance in the 2-story large homes. The VarRe controller has reasonably stable ventilation savings for both prototypes in site and TDV energy, but its savings in the 1-story homes is more than 20% lower than the VarQ controller.

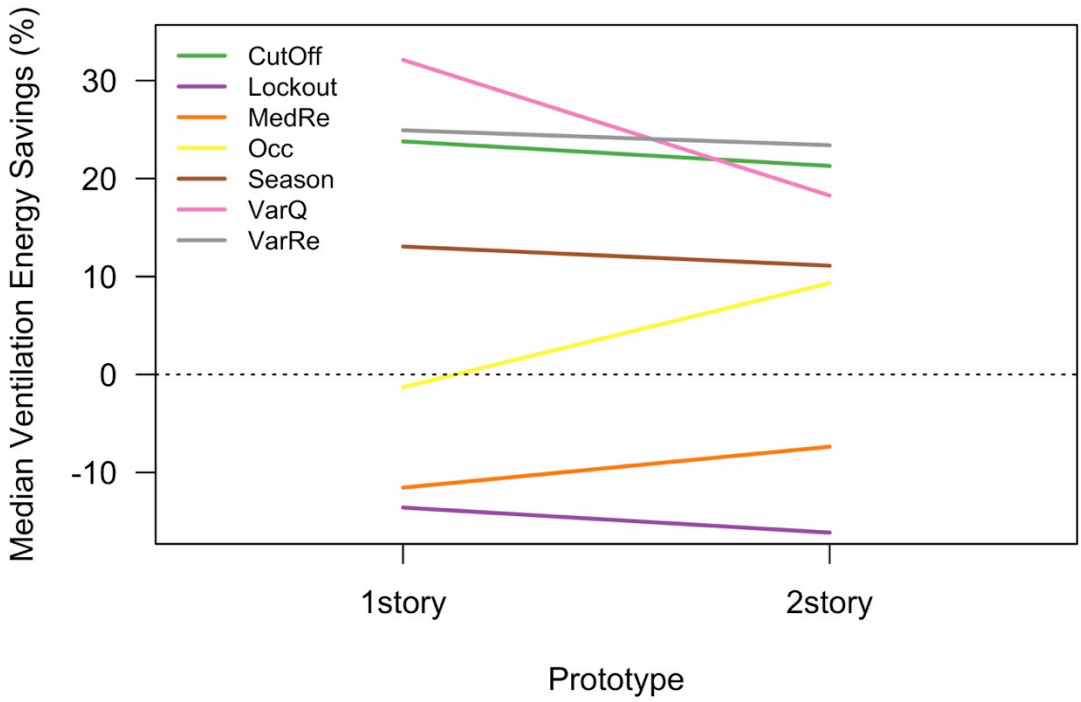

Figure 102 Median ventilation energy savings for each combination of control type and prototype.

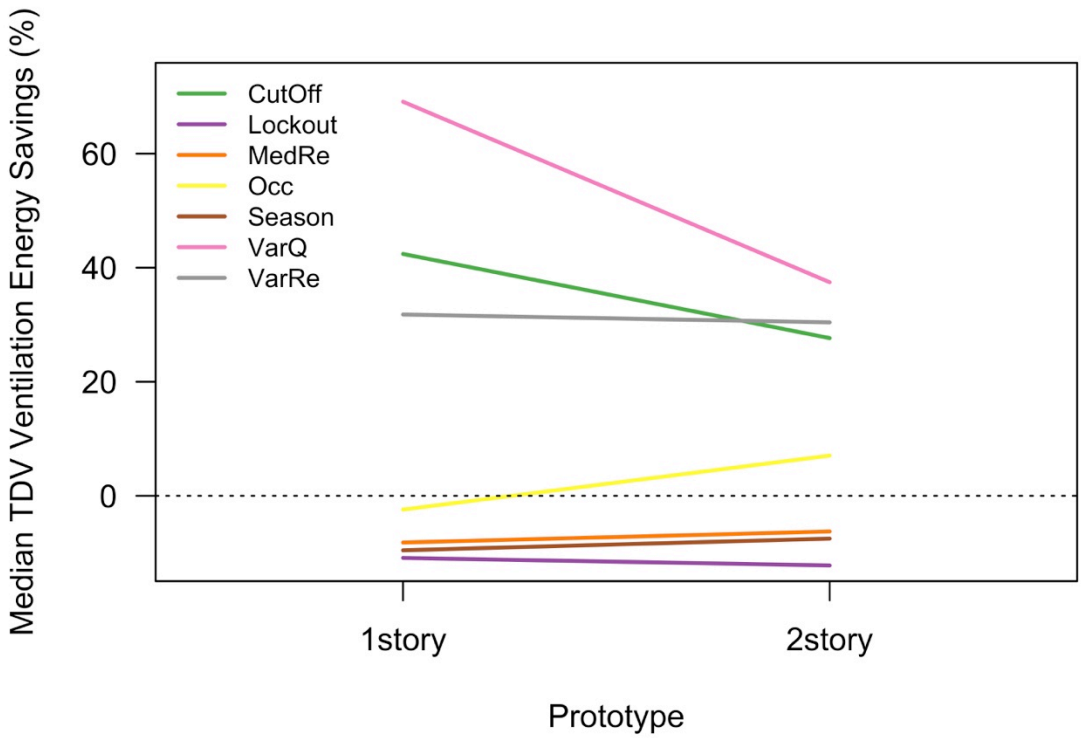

Figure 103 Median TDV ventilation energy savings for each combination of control type and prototype.

Appendix T Currently Available Ventilation Controllers

The table below represents a market search for ventilation control technologies that are currently available and include some amount of controls based on sensing of temperature, humidity or other inputs. It does not include simple timer-based controls or controls that meet ventilation standards, but do not offer sensor integration with the controls.

Manufacturer	***Product/Model #***	***Cost***	***RH Sensor***		***Temperature Sensor***		***Main Link***	***"Smart" Control Functions and Description***
			In	***Out***	***In***	***Out***		
Field Controls	Fresh Air Ventilation Control	$100	x			x	https://www.fieldcontrols.com/fresh-air-ventilation-control?page_id=92	Control up to 4 appliances, including dampers, ERV/HRV, HVAC central blower and various exhaust fans. Climate modes: Normal, Hot, Cold or Disabled. They have relations of indoor RH and outside temperature at which they either eliminate all venting, restrict to 25% of target, or vent fully. Optionally monitoring bath and laundry exhaust, etc. using pressure or current sensors, which credits against airflow requirement! 30-minute ventiing decision. Hot Climate: off <25F, during heating but limited to 25% of target 25-32F, during heating only 32-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F. Cold Climate: off <0F, during heating but limited to 25% of target 0-25F, during heating only 25-50F, normal venting from 50-90F (with indoor RH limits), 25% 90-100F, off >100F. "Normal" Climate: off <17F, during heating but limited to 25% of target 17-25F, during heating only 25-40F, normal venting from 40-90F (with indoor RH limits), 25% 90-100F, off >100F.
Honeywell	TrueIAQ	$55	x	x	x	x	https://customer.honeywell.com/en-US/pages/product.aspx?cat=HonECC+Catalog&pid=DG115EZIAQ/U	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). Vent Shut Offs: 0=Auto vent regardless of outdoor conditions 1=Off at 75°F dew point or 99°F air temp 2=Low speed at 65°F dew point or 85°F air temp. Off at 75°F dew point or 99°F air temp Note: If option 1 or 2 is selected, then ASHRAE 62.2 Standard will not be met.
Honeywell	Vision Pro IAQ	$280	x		x	x	https://forwardthinking.honeywell.com/products/the	Controls humidifier, dehumidifier, whole house and local exhaust fans. ASHRAE 62.2 fan controls. Day/night timer-based ventilation. Manually enter # of bedrooms and floor area (or cfm for 62.2). There is an indicator on the thermostat saying it "P" or "F" 62.2. Ventilation control 0 No ventilation 1 Ventilation always allowed 2 Ventilation not allowed

							rmostats/visionpro/visionpro_iaq.html	during sleep period 3 Vent all with lockouts 4 Vent off sleep with lockouts. Select high, low or both ventilation lockouts for temperature. 90 to 110 by 5F. -20 to 0F by 5F. Also, high indoor humidity control can increase ventilatino in heating mode.
Aprilaire	8126A Ventilation System	$165	x		x	x	https://www.aprilaire.com/whole-house-products/ventilation/model-8126a	CFIS only. 62.2-2010 target airflows. High and low temperature cutoffs. Humidity control with high indoor RH limit and corresponding behavior based on outdoor temp. Default is to turn venting off <0F, allow with heating operation between 0 and 20F, otherwise on but with humidity limits. Turns off >100F. Between 50 and 100F, humidity dependent with 55% indoor RH cutoff (so no ventilation "drying" is allowed). 90F high limit for "warm" climate setting. They've got good outdoor temp vs. indoor RH figures showing control operation.
Broan/Venmar	Altitude/Platinum Controller	$180			x	x	https://www.venmar.ca/224-accessories-air-exchangers-accessories-altitude-wall-control.html	CFIS only. Low temp cutoff -40 to 32F. High temp cutoff 33 to 104F.
Broan/Venmar	X-Touch/Gold-Touch	$120	x			x	https://www.venmar.ca/508-accessories-x-touch-wall-control-40455.html	CFIS. Indoor RH controller increases AER when exceeding limits, manual tells user to turn this dehumidistat feature off during cooling season. One of five CFIS speeds is selected by the controller depending on combination of indoor RH and outdoor temperature.
AirKing	QuFresh	$260 (includes fan)		x		x	http://www.airkinglimited.com/page/qfam-fresh-air-machine.html	Supply Fan, 40-120 cfm. Energy Saving Mode, allows user to configure upper and lower limits for temp and rh

Build Equinox	CERV2	Unknown	x	x	x	x	http://www.buildequinox.com/cerv2/	Integrated CO2 and VOC measurement and ventilation control. Integrates on-board heat pump rather than traditional ERV heat exchanger, to provide boost heating/cooling in recirc mode. MERV13 standard filtration. Can recirc and condition, ventilate and condition, just ventilate, or turn off. Seems like there are CO2 and VOC thresholds set by user, which the system then controls to. This limit-based approach can be combined with scheduled or continuous ventilation, as well.
Broan/Venmar	FIN-180P	Unknown		x		x	http://www.broan.com/Fresh-Air-Systems/Supply-Fan/Fresh-In%E2%84%A2-Supply-Fan/FIN-180P#resources	Supply fan, 25-180 cfm. Continuous option, otherwise 5 comfort settings based on climate zone. A sophisticated algorithm selects the best time of the day for ventilation and takes advantage of air handler usage. MERV8 or MERV 13 filter. High and low cutoffs for outside temperature and dew point, vary by climate zone (covering CZ1-4). Low end 40F cutoff with 23F Dewpoint upper limit between 85 and 90F, dewpoints of 73-75F. There are separate temperature settings if a heating/cooling call exists, it looks like they preferentially ventilate during heating/cooling calls.
Ultra-Aire	DEH 3000/3000R	Unknown	x	x		x	https://www.ultra-aire.com/deh-30003000r/#health5c24-870a	Designed to integrate with the Ultra-Aire line of whole house ventilating dehumidifiers and allows homeowners to precisely monitor and control moisture levels, manage fresh air ventilation (with optional damper), and activate air filtration. Can lock dehumidifier in with or out when cooling calls occur. There is only a high temperature cutoff, no low temp option.
AirCycler	TempGuard	Unknown				x	https://www.aircycler.com/pages/tempguard	Cold off temperature, 35F +/- 5F. Hot off temperature, 95F +/- 5F.

Table 39 Descriptions of currently available ventilation technologies that enable control based on temperature, humidity or other inputs. Note: none of these are designed to maintain equivalent exposure, as required by the ASHRAE 62.2-2016 ventilation standard.