Title

Smart Ventilation Controls for Occupancy and Auxiliary Fan Use Across U.S. Climates

Authors
Walker, IS
Less, B

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Brennan Less & Iain Walker, 2017

Building Technologies and Urban Systems Division
Whole Building Systems Department
Residential Building Systems Group

Disclaimer

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Abstract

Smart Ventilation has been developed as a way to reduce the energy associated with ventilation by changing when ventilation happens and how much ventilation occurs at any given time. In high performance buildings with low envelope and appliance related loads, ventilation is becoming a bigger part of the total building energy use and needs to be addressed if performance targets are to be met.

This work explores the development and performance of smart ventilation controls based on occupancy and auxiliary fan operation that provide annual dwelling unit ventilation equivalence to ASHRAE Standard 62.2-2016. A prototype high performance home compliant with U.S. DOE Building America Zero Energy Ready program requirements was simulated using the REGCAP tool with and without smart controls across 15 U.S. DOE climate zones. Balanced and unbalanced IAQ fans were independently simulated, and all smart controlled fans had airflows double the reference 62.2-2016 airflow. Three idealized occupancy patterns were examined: 1st shift (a typical daily work/school absence), an extended 1st shift with more time spent out of the home evenings and weekends and 3rd shift (night work). The Occupancy controller turns the IAQ fan off during unoccupied periods, and it resumes ventilation upon their return. While unoccupied, contaminants are allowed to accumulate in the space, because occupants are not exposed to these contaminants. When occupants return home, they are exposed to these higher contaminant concentrations, and the controller increases the ventilation rate sufficiently to ensure equivalence with a continuous IAQ fan. Accounting for pollutant emissions that occur during unoccupied periods (as required by ASHRAE 62.2-2016), sharply distinguishes our occupancy controls from past Demand Controlled Ventilation systems. This new accounting method results in equivalent contaminant exposure, as well as lower reductions in average ventilation rates and lower energy savings.

Smart controls were demonstrated that saved HVAC energy (i.e., avoided heating/cooling load, as well as fan energy)—averaging between 6 and 46% of ventilation-related energy use depending on the control strategy and occupancy pattern assumptions. The greatest savings were in the combined Auxiliary Fan + Occupancy control. Energy savings increased with climate heating demand and longer unoccupied time periods. The 3rd shift occupancy pattern had better performance, due to the thermal benefit of reducing the ventilation rate during the cold nighttime hours. This same effect provided a cooling energy benefit in hotter locations for the 1st shift.

Overall, savings from occupancy-based smart controls were low, because of the recovery period required after occupants return home, during which the airflow is double the 62.2 reference. This recovery is required to maintain equivalence with the ASHRAE standard. Occupancy-based control performance was improved when combined with sensing auxiliary fans and when providing a pre-occupancy flush out of one- or two-hours. Performance was similarly improved if the ASHRAE Standard were to recognize that pollutant emissions are lower during unoccupied periods,

allowing a lower *target* ventilation rate during unoccupied periods (not currently in the standard) (see Full vs. Half AEQ in this report).

Finally, over-sized unbalanced fans that are cycled on-and-off by a smart controller (or timer) were found to substantially increase annual average air exchange and energy use relative to a continuous unbalanced fan due to the effects of superposition with natural infiltration.

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1 Introduction

While residential smart ventilation controls (SVC) that maintain equivalence with ventilation standards are a relatively new concept, the notion of controlling ventilation airflows based on occupancy has a long history. Typically this is referred to as demand controlled ventilation (DCV), and it relies on measurement of carbon dioxide (CO_2) concentrations or relative humidity in the occupied space.

Traditional DCV controls suffer from some questionable assumptions, built-in performance faults, and accuracy/reliability concerns. First, this strategy implicitly assumes that either: 1) carbon dioxide and other human bioeffluents are the only pollutants that need to be controlled, or 2) all other sources of indoor pollutants are correlated to occupancy. On top of these assumptions, DCV behave imperfectly due to time lags in the concentration response to changes in the emission rate of CO_2 or water vapor. In other words, they do not stop venting immediately after occupants leave, nor do they begin venting immediately upon their return. Systems are controlled to a low level or turned off completely during unoccupied periods, which allows the build-up of contaminants that are not bioeffluents or related to human activity in the space (e.g., formaldehyde, many VOCs, contaminants of outdoor origin, etc.). As a result, DCV do not ensure that exposure to these contaminants is equivalent to a continuous fan. An additional concern with traditional DCV is that CO_2 sensing equipment is fairly expensive, subject to long-term sensor drift and other accuracy issues that make DCV a questionable approach in occupied homes where maintenance and calibration can be assumed to be non-existent.

In this study we take a different approach. First, rather than measure CO_2, we assume that there is a way to reliably know if a home is occupied using some other means. Indicators of occupancy could include IR motion sensors, location detection via smart phone, smart meter predictive analytics, etc. A ventilation system can then be turned off (or to low airflow) during unoccupied times to reduce building heating and cooling loads. Second, unlike other DCV approaches, we include non-occupant related contaminants that are emitted whether occupants are home or not. This would include pollutants like formaldehyde and other VOCs from building materials and furnishings, which are assumed to be uniformly emitted in the occupied space at a constant rate with no other sources or sinks. These other pollutants are important because they build up during unoccupied times and need to be vented upon return of occupants. Lastly, in addition to occupancy control, we will include the effects of natural infiltration and exhaust fans (from kitchens, bathrooms and clothes dryers) on ventilation rates.

The ventilation control strategies explored in this study will use the real-time IAQ ventilation controls. These controls are an implementation of the equivalent ventilation principle (Max H. Sherman, Mortensen, & Walker, 2011a; Max H. Sherman, Walker, & Logue, 2012) that allows a time-varying ventilation rate to give the same dose and exposure to a generic continually emitted pollutant as a continuously operating constant ventilation rate. Our controls use the same relative exposure calculations found in ASHRAE Standard 62.2-2016 (ANSI/ASHRAE, 2016) based on original work by Sherman et al. (2012). For more information on the background of IAQ see Sherman & Walker (2011) and Turner, Walker, & Sherman (2014). In addition, we use the control parameter—relative dose—to aid in maintaining average occupied exposure below one (see Max H. Sherman & Walker (2011) for derivation of relative dose).

1.1 Smart Ventilation Background Principles

From past work developing and testing smart ventilation controls based on equivalence principles, we introduce a number of concepts and issues that complicate this kind of simulation effort. The main issues the reader should be aware of include:

- Equivalence-based ventilation controls, such as those allowed in ASHRAE 62.2-2016, commonly do not achieve an annual relative exposure exactly equal to one. The controls are imperfect and they interact with the simulation and controller time steps to create slight biases in the resulting exposure. As a result, controllers that target an annual relative exposure of one often vary above or below that target by 2-3%. Given this inconsistency, we have assessed any SVC as complying with the ventilation standard if annual exposure is less than 1.01. Nevertheless, this makes apples-to-apples comparisons of different controls unclear.
- Similarly, a continuous fan baseline also does not achieve an annual relative exposure exactly equal to one when using an unbalanced fan, due to differences in the forward vs. backwards implementation of superposition in 62.2. We discuss the details of this below in Section 1.1.1.
- When cycling an over-sized, unbalanced ventilation fan on and off to maintain equivalent exposure, superposition effects with natural infiltration tend to increase average airflow and energy use.
- Consistent with this, balanced ventilation fans behave very differently than unbalanced in terms of overall air exchange, relative exposure and energy use. So, we tested most smart control cases using both balanced and unbalanced fans.
- Time-varying ventilation patterns must always have higher average airflows than fixed airflow patterns in order to provide equivalent exposure. The difference in average ventilation rates increases as ventilation rates become more variable. Nazaroff (2009) explores this concept while emphasizing that the arithmetic mean air exchange rate cannot be used to estimate pollutant concentrations when the ventilation rate varies in time. For a binary example, with 50% of hours at 0.1 hr^{-1} and 50% at 1.9 hr^{-1}, he highlights that using the arithmetic average (1 hr^{-1}) would under-estimate the pollutant concentration by a factor of five relative to the harmonic mean (0.19 hr^{-1}). This means that any SVC that time shifts ventilation rates will need a higher average ventilation rate overall to maintain equivalence with the baseline continuous fan. This leads to a simple fan energy penalty, as well as a

potential air enthalpy penalty, depending on the timing of that additional ventilation.

- House and weather data do not match exactly those used to generate *wsf* factors for 62.2, which are used to estimate infiltration rates and to size IAQ fans accordingly.

In this study, we have worked to varying degrees to explore and address these issues and biases. First, as noted above, we tested nearly all controls using both balanced and unbalanced IAQ fans. Second, we use two different baselines for assessing control performance. One is simply a continuous unbalanced (or balanced) fan sized to ASHRAE 62.2-2016; this is the typical baseline that most readers would have in mind, but it has an annual exposure above one in all cases. The other is called the NULL control, which is a controller that cycles on-and-off an over-sized fan (two times baseline 62.2-2016 airflow) to maintain a relative exposure of one, with no other control inputs. This NULL baseline allows an apples-to-apples assessment of the smart control impacts, where the baseline is not biased with a relative exposure greater than one and where the superposition and effects of time varying ventilation largely cancel out in control and baseline cases. Given this, we expect the NULL control to have very similar performance to the cases using balanced ventilation fans, where effects of an occupancy-based control are isolated from other effects.

We expect that the weather files we have used, as well as our leakage distribution, roughly match those assumptions used to generate infiltration factors in ASHRAE 62.2 (see Turner & Sherman (2012)). As such, we made no real efforts to address any remaining small differences in infiltration estimates using the 62.2-2016 equations.

1.1.1 Superposition in ASHRAE 62.2-2016

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 new super-position model was presented by Hurel, Sherman, & Walker (2016). This was incorporated for fan sizing calculations by Addendum S to ASHRAE 62.2-2016, Equation 4.6. In addition to fan sizing, these super-position methods are used in estimation of total house airflow when using Normative Appendix C Relative Exposure to demonstrate compliance (as is done with smart controls). These two formulations are similar, but result in consistently different values depending on whether you are estimating fan size based on a total airflow and infiltration, or if you are estimating total airflow based on fan size and infiltration.

Both methods calculate a phi value, which is used to adjust the infiltration estimate when using unbalanced ventilation fans. The "backward" formulation is used in fan sizing:

$$\emptyset_{backward} = \frac{Q_{inf}}{Q_{tot}} \quad (1)$$

$$Q_{fan} = Q_{tot} - \emptyset_{backward} \times Q_{inf} \quad (2)$$

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

$$\emptyset_{forward} = \frac{Q_{inf}}{Q_{inf} + Q_{fan}} \quad (3)$$

$$Q_{house} = Q_{fan} + \emptyset_{forward} \times Q_{inf} \quad (4)$$

For nearly any example set of values, Q_{house} is not equal to Q_{tot}. 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 1 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.

The fact that a continuous unbalanced fan sized using standard ASHRAE 62.2-2016 calculation methods does not give a relative exposure equal to one is problematic, given that smart controls are required to achieve one or less. This is particularly troublesome, because as we see in Figure 1, the bias is always towards the continuous fan having an exposure greater than one. Any smart fan attempting to show compliance with the standard must first increase ventilation relative to the continuous fan baseline (to get exposure <= 1), before even implementing any controls whatsoever. This acts as an energy disadvantage for the SVC. Balanced ventilation fans are not subject to the superposition equations in 62.2-2016, so do not suffer from this bias in sizing or house airflow estimation.

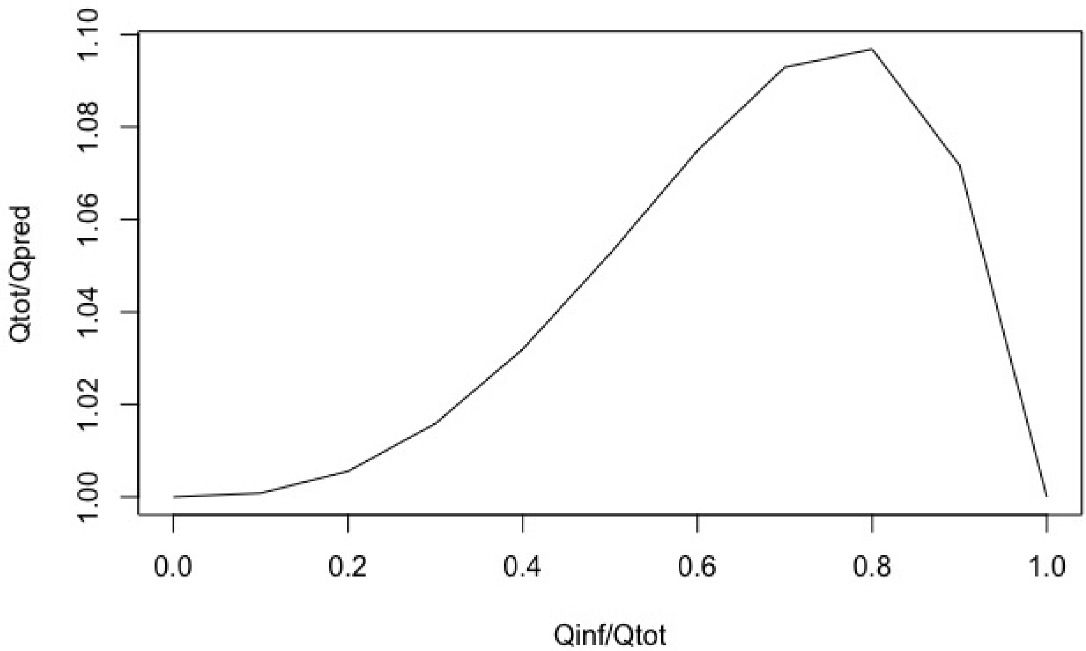

Figure 1 Illustration of bias in the ASHRAE 62.2-2016 unbalanced fan sizing calculation.

1.1.2 Superposition and Cycling Fans

Not only does superposition affect the relative exposure of a baseline continuous fan case, it also affects any controller that is cycling an over-sized fan on-and-off to maintain a relative exposure of one (or any over-sized IAQ fan that cycles on a timer, such as CFIS). In this situation, average airflow is increased due to super-position.

In Figure 2, we show the natural infiltration without mechanical ventilation operating (0.5 hr^{-1}) and the fan airflow (1.0 hr^{-1}). The combined, sub-additive airflow is given by Equation 6 as 1.17 hr^{-1} (not 1.5 hr^{-1}).

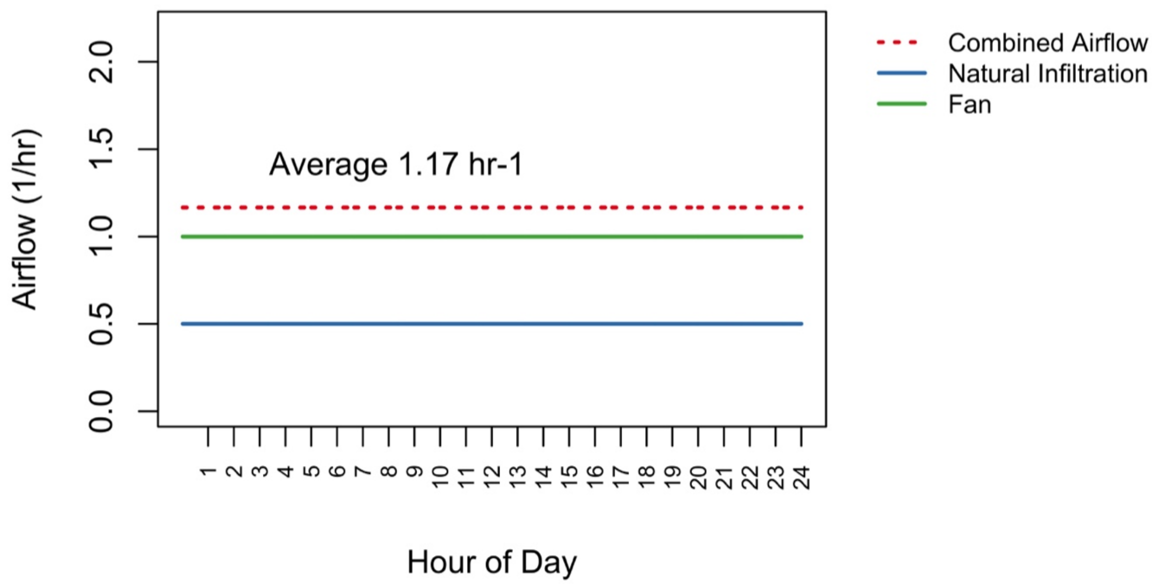

Figure 2 Illustration of an unbalanced continuous exhaust fan combined with a fixed infiltration rate.

Figure 3 shows how the same natural infiltration of 0.5 hr^{-1} combines with a cycling fan airflow of either 0 or 2.0 hr^{-1} that operates for only half the time – one for an hour then off for an hour. When the fan is on, it is dominant, and the combined airflow is 2.1 hr^{-1} (purple line). The arithmetic average is 1.3 hr^{-1} compared with 1.17 hr^{-1} for the continuous fan. If we control the fan using an IAQ controller to meet an equivalent exposure of one, the average airflow rate is also greater than the continuous fan: 1.24 hr^{-1}. The average airflow remains greater, because IAQ controls on relative exposure to maintain equivalence, and relative exposure is proportional to the inverse of the air exchange rate. In this case, achieving equivalent exposure means biasing house airflow upwards from 1.17 to 1.24 hr^{-1}, roughly a 6% increase.

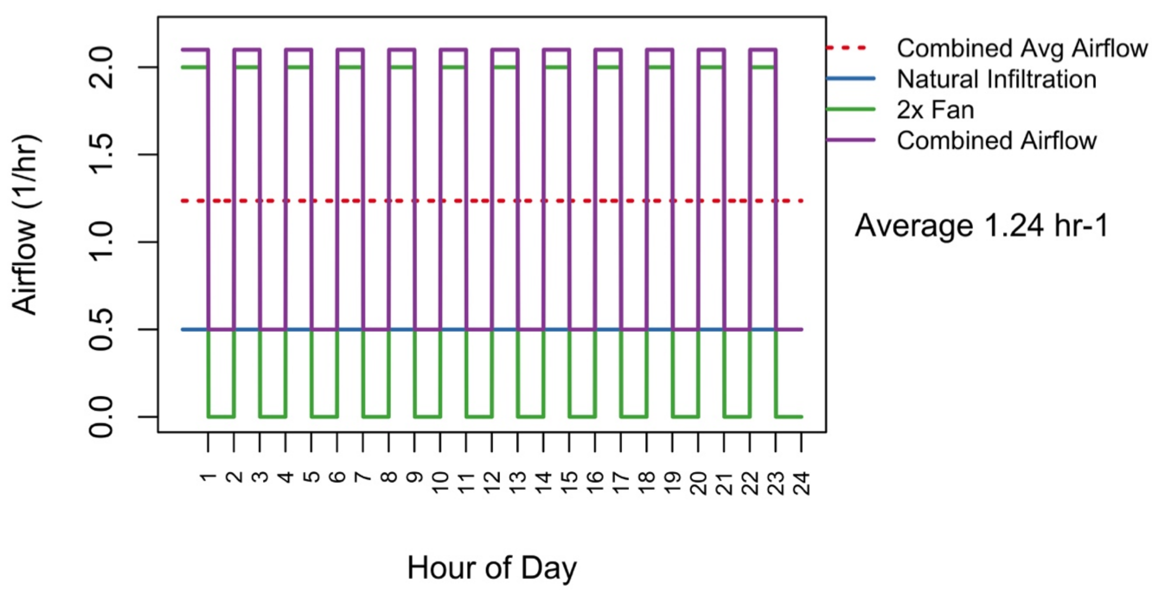

Figure 3 Illustration of an unbalanced over-sized exhaust fan combined with a fixed infiltration rate.

2 Literature Review

We first reviewed extant literature on the use of smart ventilation controls in residences. Studies which have been done to date exclusively focus on CO_2-based or relative humidity-based DCV, and thus the following review of literature encompasses only this portion of the problem. These are fundamentally distinct from the Occupancy approach we will use, which will focus on an occupancy signal (binary yes or no), and which accounts for pollutant emission from non-occupancy sources.

2.1 CO_2

Indoor air variables such as odors, temperature, CO_2 and humidity strongly correlate to occupant presence and activities, and can also be important to consider in a smart ventilation approach. CO_2 and relative humidity are the most commonly used parameters in demand-controlled ventilation systems. Their ability to represent overall indoor air quality, including their correlation with other types of indoor pollutants, has been partially studied in the literature.

CO_2 is often used in DCV strategies, not to prevent negative health effects directly attributed to it, but because it is relatively easy to measure and often correlates well with other parameters such as concentrations of bio effluents and other indoor air pollutants, and ventilation rates. It is generally acknowledged that health effects directly attributable to CO_2 are minimal at concentrations observed in indoor environments, which are commonly in the range of 350-2000 ppm. One of the sole exceptions was an experimental study by Allen et al. (2015) on 24 human subjects that suggested an effect on psychomotricity performance above 1,000 ppm attributable to CO_2, but which must still be investigated further according to the authors. A more recent study by Zhang, Wargocki, & Lian (2017) was able to disaggregate the effects of CO_2 and bio-effluent exposure, and their results suggest that exposure to moderate concentrations of bio-effluents and metabolically generated CO_2, will affect occupants at typical indoor exposure levels.

Recent studies (ANSES, 2013; Ramalho et al., 2015) have demonstrated that CO_2 concentrations in homes were significantly correlated with concentrations of other pollutants such as acetaldehyde, formaldehyde, benzene, acrolein, $PM_{2.5}$ and PM_{10} but that the correlations were weak, and sometimes very weak. Research in this field needs to be consolidated before concluding with a high degree of confidence that CO_2 concentrations are significantly correlated with other indoor air pollutants for smart ventilation applications.

In his review on demand-controlled ventilation, (Raatschen, 1990a) affirmed that according to the analyzed literature "*there is no doubt that CO_2 is the best gas to use in a ventilation system when a building is occupied and no other large pollution sources such as smokers are present*". Yet, ten years later, in their review on CO_2-based DCV, Emmerich & Persily (2001) underline the limitations inherent in using CO_2 because of its inadequacy as an overall indicator of IAQ, especially for pollutant emission from sources other than occupants, such as building materials and furnishings. Nevertheless, they justify the use of CO_2 as an indicator of ventilation rate per person, based on regulations or standards. Indeed, existing standards and regulations are largely been based on CO_2, paying specific attention to the threshold of 1000 ppm (Max von Pettenkofer, 1858) and the well-described relationship between ventilation rate and indoor CO_2 concentration.

2.2 Demand Controlled Ventilation

Most demand controlled ventilation systems detailed in the research literature use indoor relative humidity as the control parameter, while some more recent approaches have used CO_2 or occupancy. Notably, the use of moisture and CO_2 in a DCV strategy implicitly ignores the emissions of non-human bioeffluents that may occur during unoccupied time periods or periods of reduced occupancy or reduced activity pattern. If emitted in the home, these non-occupant related emissions will continue to accumulate during unoccupied times, and exposure to these contaminants will not be controlled to be equivalent with a continuous ventilation fan. In fact, this is exactly what Hesaraki & Holmberg (2015) found for unoccupied periods exceeding 4-hours in a new home, VOCs rose to unacceptable levels. The occupancy control explored in this research is distinguished from past efforts, in that it explicitly accounts for background emissions.

Three past literature reviews on DCV across building types and contexts have included a total of 15 papers concerning DCV in residences (Chenari, Dias Carrilho, & Gameiro da Silva, 2016; Fisk & De Almeida, 1998; Raatschen, 1990b). Currently, the California Energy Commission SVACH project is developing next generation smart ventilation controls in single- and multi-zone contexts for new California homes, and this project has completed a not-yet-published review covering an additional 23 papers related to residential DCV. The authors stress that comparing the results of studies is extremely difficult due to lack of consistency in baseline ventilation rates, inconsistent reporting of environmental conditions and use of widely varying metrics to assess performance.

Occupancy-based controls have also been assessed in some research projects with substantial estimated energy savings reported. For example, Romer & Van Ginkel (2003) reported on a preliminary TRNSYS-modeling study, which demonstrated energy savings of about 20% for occupancy based ventilation control. Such a system was also installed in a test house. In a recent modeling study of a new 3-level house in Sweden, (Hesaraki & Holmberg, 2015) studied the IAQ and energy impact of a whole-house exhaust-only DCV system based on occupancy, considering unoccupied periods of 4,6, 8, and 10 hours. The whole-building airflow rate is 60 L/s (0.75 L/s-m^{-2}) and is switched to 16 L/s(0.1 L/s-m^{-2}) during unoccupied periods. They found that unacceptable IAQ occurred in the home with unoccupied periods longer than 4-hours due to accumulated indoor-emitted VOCs, and they recommend an increase in the unoccupied ventilation rate. With a 10-hour absence, turning the system to normal speed two hours prior to occupancy led to acceptable IAQ conditions. The heating energy savings was estimated at 20% and fan consumption 30%. As a result, the total building energy consumption was reduced by 10%, from 52 to 47 $kWh.m^{-2}$. Similarly, Laverge, Bossche, Heijmans, & Janssens (2011) found a reduction in ventilation heat loss of 25-60% relative to a continuous exhaust system, using several DCV strategies in a simulated multi-zone home statistically representative of the average Belgian dwelling.

A number of studies from LBNL have demonstrated the applicability of an intermittent ventilation strategy for residential buildings based on occupancy. The concept of equivalence in exposure was primarily developed considering such strategies (M.H. Sherman, 2004) and has been integrated into previous updates of the ASHRAE 62.2 standard (2016). Later, (Max H. Sherman, Mortensen, & Walker, 2011b) further developed this concept to apply under a variety of ventilation rates, emission rates and the evaluation periods for the dose.

Based on this background for chronic and acute exposure evaluation, (Mortensen, Walker, & Sherman, 2011a) studied the optimization of the performance of a whole-house ventilation strategy with two fan speeds. They studied variations in the emission ratio- defined as the ratio between all pollutant source strengths and background pollutant source strength; the low ventilation factor- defined as the ratio between the low ventilation rate and the ventilation rate of the equivalent constant rate system; and this equivalent constant rate. They show that the performance can always be optimized given the occupancy time and emission characteristics. The low-ventilation factors were 0.13-0.4 at peak effectiveness, and all the systems had a high-to-low flow airflow ratio of 2.5-5. They also calculated the ratio of the acute to the chronic exposure and showed that it was always less than 3, which means such DCV systems provide also for acceptable peak exposures. They have shown that for a home occupied for 16 consecutive hours, the total ventilation rate reduction is about 12% compared for equivalence to a target constant rate of 0.5 h^{-1} and an emission ratio of 1.5. At the extreme case when occupant pollutant emissions are dominant the reductions can be about 18%. At the other extreme, where there is no contribution to contaminant emissions from occupants this is reduced to 9%.

3 Method

3.1 Test Homes and Simulation Tool

All simulations assume a single-story, 200-m^2 (2,153 ft^2) home with three bedrooms, two bathrooms and four occupants. The homes are compliant with the energy and performance specifications of the U.S. DOE Zero Energy Ready Home program (U.S. Department of Energy, 2013). These include thermally efficient envelopes (R-13 to R25 walls), high performance HVAC equipment (80 to 94 AFUE heating, SEER 13 to 18 cooling) and airtight construction (1.5 to 3 ACH_{50}).

The REGCAP simulation tool was used to predict the ventilation and energy performance. It combines detailed mass-balance models for ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. The details of this model have been presented elsewhere (Iain S. Walker, 1993; Iain S. Walker & Sherman, 2006; I.S. Walker, Forest, & Wilson, 2005), along with validation summaries of house and attic air, mass and moisture predictions. Two zones are simulated: the main house and the attic. With a single conditioned house zone, only single-point exhaust or balanced fans were simulated, and no effort was made to assess ventilation effectiveness by location in the home. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance.

Three rounds of simulations were performed, each including different sets of assumptions about IAQ fan type and occupant pollutant emissions. These are summarized in Table 1 and are described in further detail in the subsections below. We tested control performance with unbalanced exhaust fans, (Full AEQ) as well as balanced ventilation fans without heat recovery (Balanced). To examine the potential impact of assuming reduced emission rates when the home is unoccupied we repeated the simulations with the unbalanced fans, assuming that target ventilation rates that were halved when the home was unoccupied (Half AEQ). These target rate assumptions are discussed in detail in Section 3.6. As noted in the Introduction and listed in Table 1, we used two different baseline cases—continuous unbalanced fan and NULL control—to assess control performance for unbalanced IAQ fans. The term "AEQ" refers to the target ventilation rate established by the ASHRAE 62.2-2016 ventilation standard for a home of given size and number of bedrooms (referred to as Q_{tot} in the standard). This is the total house airflow (i.e., combined fan and natural infiltration) that a controlled fan must maintain equivalence with.

Simulation Round	***IAQ Fan Type***	***Baseline***	***Pollutant Emissions***
Full AEQ	Unbalanced exhaust	1) Continuous balanced fan sized to 62.2 size 2) NULL Control, fan double 62.2 size	Fixed
Half AEQ	Unbalanced exhaust	1) Continuous balanced fan sized to 62.2 size 2) NULL Control, fan double 62.2 size	Variable with occupancy
Balanced	Balanced fan without heat recovery	1) Continuous balanced fan sized to 62.2 size	Fixed

Table 1 Summary of the fan types and baseline cases used in each simulation round.

For each simulation round (Full AEQ, Half AEQ and Balanced) and each prototype house (15 DOE climate zones 1 – 8), five simulations were performed:

(1) Baseline with no IAQ fan, but with auxiliary fan operation (i.e., kitchen, bath and clothes dryer exhausts),
(2) Baseline with IAQ fan and auxiliary fan operation,
(3) Over-sized fan with IAQ control based on **auxiliary fan operation**,
(4) Over-sized fan with IAQ control based on **occupancy**, and
(5) Over-sized fan with IAQ control based on **auxiliary fan operation and occupancy**.

The initial simulation using no whole house 62.2-2016 ventilation is used only for comparison with a continuous fan operation case in order to quantify the energy use attributable to ventilation. The energy used for 62.2-2016 whole house ventilation compliance is the difference between the 2nd and 1st simulations. Energy savings for the three control types were then calculated as the difference between the energy use in the controlled cases (#3 - 5) and the relevant baseline case (#2, see Table 1). The normalized reduction in ventilation energy use is the control case savings divided by the energy use increase resulting from use of the continuous 62.2-2016 fan (or NULL control fan) (#2 – 1). All ventilation and HVAC energy use estimates include IAQ fan energy, heating and cooling loads, and air handler energy use. Our energy estimates represent the total change in household energy consumption expected from use of a smart controller.

3.2 Mechanical Ventilation Fan Sizing

The ventilation fan sizing and accounting for natural infiltration were done following ASHRAE 62.2-2016. The dwelling unit ventilation requirements are based on floor area and number of bedrooms:

$$Q_{tot} = 0.15A_{floor} + 3.5(N_{br} + 1) \quad (5)$$

Q_{fan} = required air flow rate, L/s

A_{floor} = conditioned floor area, m^2

N_{br} = number of bedrooms; not to be less than one

The required mechanical ventilation rates are reduced by the ASHRAE 62.2 infiltration credit:

$$Q_{inf} = \frac{NL \times wsf \times A_{floor}}{1.44} \quad (6)$$

Q_{inf} = effective annual average infiltration rate, L/s

NL = Normalized leakage

wsf = weather and shielding factor (from normative appendix B in ASHRAE 62.2-2016)

A_{floor} = floor area of the home, m^2

The sub-additivity coefficient (ϕ) is used in sizing the fans, which accounts for the sub-additive combination of unbalanced mechanical airflows and natural infiltration airflows. The required fan size is calculated using Equation 3, leading to different fan airflows when using balanced fans versus unbalanced exhaust fans. Balanced fans were simulated as volumetrically balanced flows, with double the fan energy use of an equal sized exhaust fan. IAQ fan power was estimated using a fixed efficacy of 0.21 Watts per cfm (0.44 Watts per L/s).

$$Q_{fan} = Q_{tot} - \varphi Q_{inf} \quad (7)$$

Q_{fan} = required mechanical ventilation rate, L/s

Q_{tot} = total required ventilation rate, L/s

Q_{inf} = effective annual average infiltration rate, L/s

Φ = 1 for balanced ventilation systems and Q_{inf}/Q_{tot} otherwise

3.2.1 Smart Control Ventilation Fan Over-Sizing

Smart ventilation controllers need to control a fan with a greater airflow than that required of a continuous fan sized according to ASHRAE 62.2-2016. It is this over-sizing that allows for the strategic time shifting of ventilation in response to control parameters, such as occupancy, outside temperature, peak electricity pricing, etc. When the ventilation rate is reduced, the relative pollutant exposure increases, and in order to reduce it back below one (i.e., recover), a greater airflow is required. In this study we have over-sized smart ventilation control fans by a factor of two (i.e., doubling the continuous fan airflow from Equation 3 above). In the 1st shift extended cases (12-hour weekday absence), this was not sufficient and controllers failed to maintain annual equivalence during occupied hours, so we increased fan over-sizing to a factor of 2.5 for those cases. We assessed the effects of varying the fan over-sizing for balanced fans (see discussion in Section 4.5.1).

3.3 Occupancy and Auxiliary Fan Schedules

Occupancy schedules are continuous, 1st and 3rd shift, and a 1st Shift Extended pattern (1st Ext) (see Table 2). The shift schedules have 9-hour workday absences (8am - 5pm and 9pm - 6am, respectively) and continuous weekend occupancy. The extended shift pattern has a longer daytime away period and also provides absence periods each weekend. All patterns are idealized and are intended to be roughly consistent with typical workday patterns.

Fan schedules are aligned with the occupancy schedules, with the same amount of fan use in all cases, but with timing aligned to mealtimes and sleep hours based on shift work (see Table 3). Fan operation includes: 40 minutes per day clothes dryer (71 L/s (150 cfm)), 40 minutes per day kitchen fan (10-min breakfast and 30-min dinner events, 47 L/s (100 cfm)), and four 20-minute bath fan events (24 L/s (50 cfm)). Total daily auxiliary fan use is fixed at 160 minutes in all cases. The fan operation events are assigned to an hour of the day, and the actual operating minutes are determined by randomly selecting the minute to begin fan operation. It then runs for the fixed event duration, which sometimes extends into an unoccupied period. This is valid for many exhaust device types, such as a vented clothes dryer that continues to operate after occupants leave, or a bathroom exhaust fan on a timer or humidistat control. This only applies to the exhaust fan cycles that occur prior to the occupants' departure from the home.

Hour of Day	*1st Shift*		*3rd Shift*		*1st Shift Extended*	
	Weekday	***Weekend***	***Weekday***	***Weekend***	***Weekday***	***Weekend***
0:00	1	1	0	1	1	1
1:00	1	1	0	1	1	1
2:00	1	1	0	1	1	1
3:00	1	1	0	1	1	1
4:00	1	1	0	1	1	1
5:00	1	1	0	1	1	1
6:00	1	1	1	1	1	1
7:00	1	1	1	1	1	1
8:00	0	1	1	1	0	1
9:00	0	1	1	1	0	1
10:00	0	1	1	1	0	0
11:00	0	1	1	1	0	0
12:00	0	1	1	1	0	1
13:00	0	1	1	1	0	1
14:00	0	1	1	1	0	1
15:00	0	1	1	1	0	1
16:00	0	1	1	1	0	1
17:00	1	1	1	1	0	1
18:00	1	1	1	1	0	0
19:00	1	1	1	1	0	0
20:00	1	1	1	1	0	1
21:00	1	1	0	1	0	1
22:00	1	1	0	1	1	1
23:00	1	1	0	1	1	1
Total Occupied	15	24	15	24	10	20

Table 2 Occupancy patterns (1 = occupied and 0 = unoccupied).

Hour of Day	*1st Shift (minutes of operation)*				*3rd Shift (minutes of operation)*				*1st Shift Extended (minutes of operation)*			
	Clothes Dryer	*Kitchen Fan*	*Bath Fan 1*	*Bath Fan 2*	*Clothes Dryer*	*Kitchen Fan*	*Bath Fan 1*	*Bath Fan 2*	*Clothes Dryer*	*Kitchen Fan*	*Bath Fan 1*	*Bath Fan 2*
0:00	0	0	0	0	0	0	0	0	0	0	0	0
1:00	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0	0	0
7:00	0	10	20	20	0	30	0	0	0	10	20	20
8:00	0	0	0	0	40	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	20	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0	20	0	0	0	0
12:00	0	0	0	0	0	0	0	0	0	0	0	0
13:00	0	0	0	0	0	0	0	0	0	0	0	0
14:00	0	0	0	0	0	0	0	0	0	0	0	0
15:00	0	0	0	0	0	0	0	0	0	0	0	0
16:00	0	0	0	0	0	0	0	0	0	0	0	0
17:00	0	0	0	0	0	0	0	0	0	0	0	0
18:00	0	30	0	0	0	0	0	0	0	0	0	0
19:00	40	0	0	0	0	0	0	0	0	0	0	0

20:00	0	0	20	0	0	10	20	20	0	0	0	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	20	0	0	0	0	0	30	20	0
23:00	0	0	0	0	0	0	0	0	40	0	0	20
Total Daily (min)	***40***	***40***	***40***	***40***	***40***	***40***	***40***	***40***	***40***	***40***	***40***	***40***

Table 3 Auxiliary exhaust fan operation schedules for 1st and 3rd shift patterns.

3.4 IAQ Assessment - Relative Exposure and Dose

Compliance with ASHRAE Standard 62.2-2016 is assessed for the smart control cases using relative exposure calculation procedures from Appendix C of the standard. Continuous fans sized to 62.2-2016 comply with Section 4 of the standard. However, following Appendix C calculations, continuous fans do not necessarily achieve the Appendix C requirement of annual relative exposure less than or equal to 1. This is due to small differences between the *forward* and backward formulations, as described in Introduction Section 1.1.1. Real-time smart control cases with double the fan airflow capacity are controlled such that the annual average relative exposure is equal to or less than one. More details on the derivation of the *forward* and *backward* solutions are given in (Hurel et al., 2016).

The IAQ ventilation controller used in these simulations decides when to operate the ventilation fan based on calculated values for relative exposure and relative dose, which track the real-time comparison between the time-varying and fixed ventilation rates provided by a continuous fan sized to 62.2-2016. The relative dose and exposure calculations are performed once every minute, and a control decision is made once every 10 minutes. Relative exposure is the metric used in ASHRAE 62.2-2016 to determine compliance with Appendix C. Annual average relative exposure must be less than or equal to one. Relative dose is a control parameter used in our simulations to aid in maintaining daily occupied exposure equal to one; it is essentially a 24-hour running average of the exposure.

The relative exposure for a given time step is calculated from the relative exposure from the prior step and the current and target ventilation rates (Q_i and Q_{tot}) using Equation 4, unless the real-time or scheduled ventilation is zero, then Equation 5 is used. In our simulations, the current ventilation rate is a simplified value that is calculated using the fixed annual average infiltration estimate from ASHRAE 62.2 (Q_{inf}, see Equation 2) and the current fan airflow including both the whole dwelling unit fan and auxiliary fans. These two flows are combined using the *forward* sub-additive approach in 62.2, as in Equation 6.

$$\boldsymbol{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right)e^{-Q_{tot}\Delta t / V_{space}}} \qquad (8)$$

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, also referred to as *Aeq,* m^3/s
Q_i = Ventilation rate from the current time-step, m^3/s
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, m^3

$$\boldsymbol{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \qquad (9)$$

$$Q_i = Q_{fan,i} + \varphi\, Q_{inf} \quad (10)$$

Q_{inf} = effective annual average infiltration rate, m^3/s

Φ = 1 for balanced ventilation systems and $Q_{inf}/(Q_{inf} + Q_{fan})$ otherwise

$Q_{fan,i}$ = mechanical ventilation rate at current time step, m^3/s

The relative exposure reflects the real-time ratio between the concentration of a generic, continuously emitted indoor contaminant under two ventilation rates. First, is the fixed ventilation rate equal to Q_{tot}—this is called the AEQ (See Equation 1). The second rate is the real-time ventilation rate. A relative exposure equal to 1 means the two ventilation rates are equivalent. Values less than one reflect higher ventilation relative to the reference airflow rate, and values above one reflect lower airflow. A relative exposure of one-half suggests the real-time ventilation rate is double the reference ventilation rate, and a relative exposure of two indicates a real-time ventilation rate that is half the reference rate. Annually, the average during occupied hours of the relative exposure must be less than or equal to one in order to satisfy ASHRAE 62.2-2016 Appendix C requirements.

The relative exposure provides a snapshot of the ventilation rates at an instant in time, but it does not allow a controller to operate a fan to maintain an average exposure equal to one. IAQ uses a second control parameter, the relative dose, which is a 24-hour integrated average of the relative exposure. Relative dose is calculated using:

$$d_i = r_i * \left(1 - e^{\frac{\Delta t_{rivec}}{24}}\right) + d_{i-1} * e^{\frac{\Delta t_{rivec}}{24}} \quad (11)$$

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_{IAQ} = IAQ time-step, hr.

3.5 Smart Ventilation Control (SVC) Strategies

3.5.1 Auxiliary Fan SVC

The Auxiliary Fan SVC is a real-time IAQ control that includes the operation of other exhaust fans in the home in Q_i and operates the ventilation fan based on calculated relative dose and exposure as shown in Table 4. 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 4 Control details for Auxiliary Fan SVC.

An example of how the SVC responds to auxiliary fan operation is shown in Figure 4 for a 1st shift Baltimore home. The blue line shows the ventilation rate through the whole house IAQ fan. This fan generally cycles on and off to control relative exposure to one. The cycling of this fan stops during times with auxiliary fan use (shaded aqua, green line), because these auxiliary flows are counted in the house airflow used in the exposure calculations. Shortly after auxiliary fan events, the whole house fan begins to cycle on and off once more, as relative exposure returns above one. Here we see how the whole house IAQ fan turns off for roughly two-hours in response to the auxiliary fan operation.

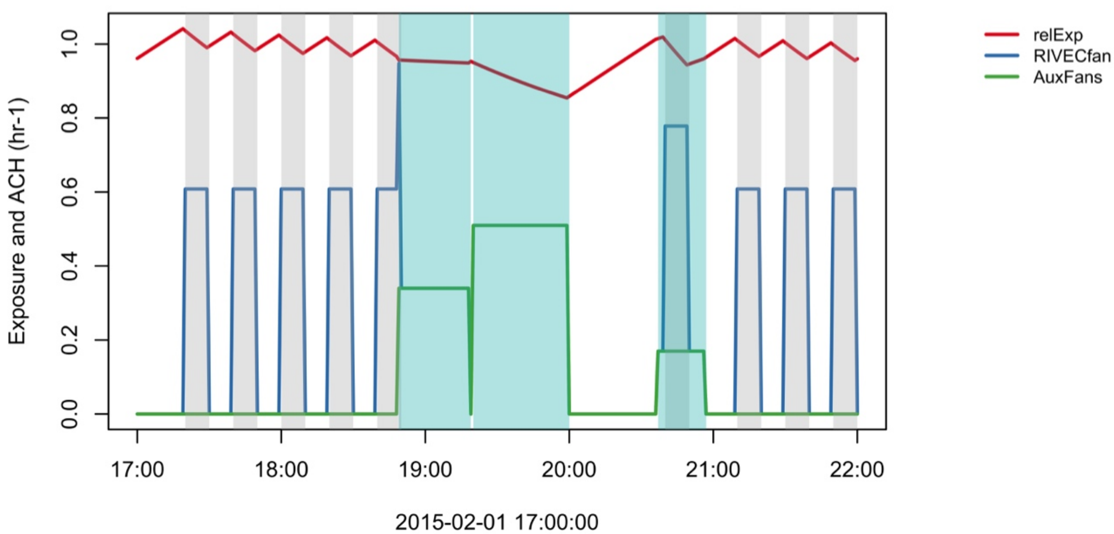

Figure 4 Illustration of Auxiliary Fan control operation in Baltimore home with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey and auxiliary fan operation in aqua.

3.5.2 Occupancy SVC

The Occupancy SVC is a real-time IAQ control that responds to the occupancy of the home and shuts off the ventilation fan during unoccupied periods (see Table 5 for control details). During this 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 then bring relative exposure and relative dose below one by ventilating the house at a higher rate. 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 5. 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.

	Fan ON Conditions	
Control Variable	***Occupied***	***Unoccupied***
Relative Exposure	>1	>5
Relative Dose	>1	NA

Table 5 Control details for the Occupancy SVC.

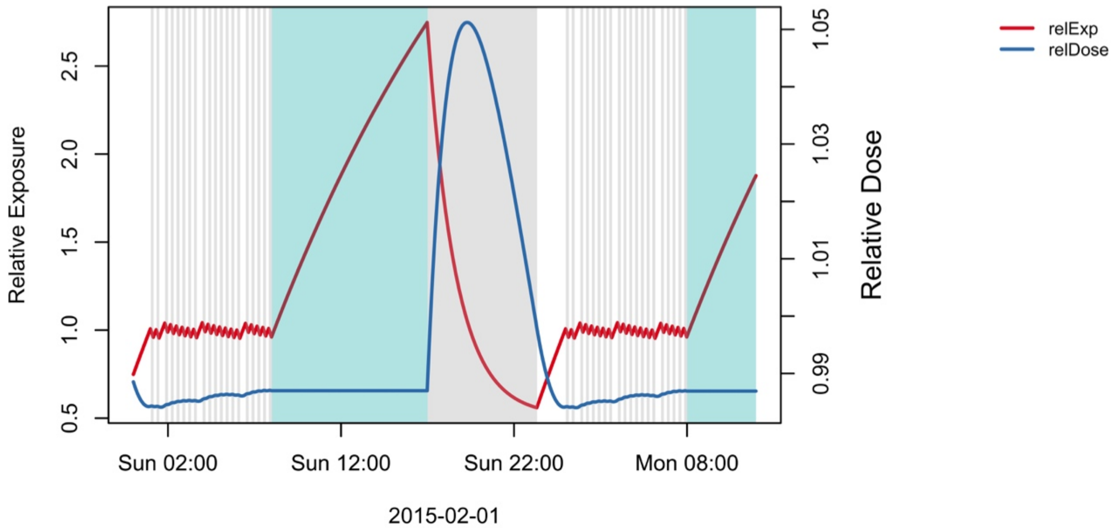

Figure 5 Illustration of Occupancy control operation in Baltimore home with 1st shift occupancy schedule. IAQ fan periods highlighted in light grey, unoccupied period in aqua.

3.5.3 Occupancy + Pre-Occupancy Flush Out SVC

We also tested a version of the occupancy controller where the controller can predict when occupants will return home. In these example cases, the controller turns on the mechanical ventilation system before occupants return home. This was tested for one- and two-hour pre-occupancy flush out periods, during which the smart controlled fan is operated at double the 62.2 airflow. This approach should reduce occupant peak exposure, lessen the recovery period and save energy. This pre-occupancy flush out was tested only for 1st shift cases using the Full AEQ pollutant emission assumption with unbalanced exhaust fans.

3.5.4 Occupancy + Auxiliary Fan SVC

The Occupancy + Auxiliary Fan SVC combines the two approaches outlined above and uses the same control criteria as Table 5, such that auxiliary fans are accounted for in house ventilation rate calculations, and the IAQ fan is turned off during unoccupied periods. The auxiliary fan accounting serves to shorten the recovery period because much of the daily auxiliary fan operation is scheduled for the evening hours after occupants return home.

The operation of the combined SVC strategy is compared with the solely occupancy-based control shown in Figure 6. During unoccupied hours between 8am and 5pm, controls based on occupancy turn off the ventilation fan and allow the relative exposure to increase. This particular 9-hour absence leads to a peak relative exposure of 2.7. When occupants return, the ventilation fans are turned on (doubling the ventilation rate relative to the baseline). This higher ventilation rate is maintained until the integrated relative exposure is less than one. During this decay period, the decay rate of the occupancy control is fixed (red line), whereas the decay rate for the combined control (blue line) increases during operation of other exhaust fans (green line). This drives the relative exposure down faster and lessens the higher ventilation decay period. Pink highlighted region shows the shorter recovery period when accounting for auxiliary fan operation (Occ+AuxFan), and green highlighted region shows the further recovery time for the standard control (Occupancy).

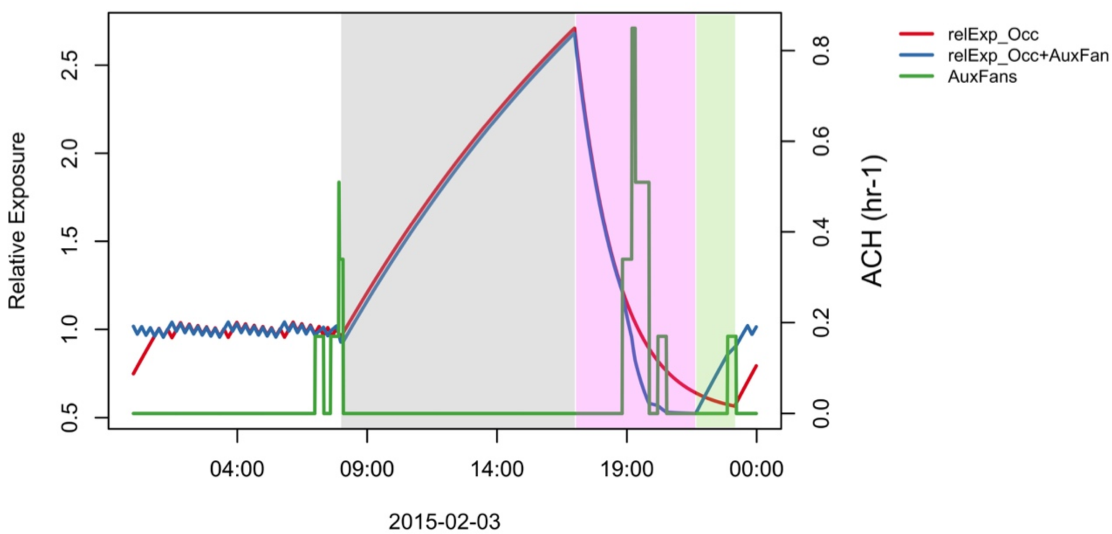

Figure 6 Time-series illustration of the Occupancy vs. the Aux Fan + Occupancy controllers. Baltimore example home with 1st shift pattern. Unoccupied period in light grey, Occupancy recovery period in pink, and AuxFans+Occupancy recovery period in green.

3.6 Target Ventilation Rate During Unoccupied Periods—Full vs. Half AEQ

Past work using relative dose and exposure to assess the potential for demand controlled ventilation in residences has summarized the scope of the expected benefits (Mortensen, Walker, & Sherman, 2011b). Mortensen et al. explored varying occupancy patterns, ventilation fan sizing and ratios of occupied vs. unoccupied pollutant emission rates. They confirmed the premise that equivalence could be maintained while reducing the total integrated airflow relative to a baseline continuous fan. For cases with constant pollutant emissions that did not vary with occupancy, a reduction in total air volume of 9% was estimated, but with occupant-dominated emissions (four times the unoccupied emission rate), the reduction in airflow increased up to about 18%.

While clearly emission may be lower during unoccupied periods, the crucial question is: *what happens during occupied hours*? If one believes the requirements of the ASHRAE 62.2 Standard have averaged occupant pollutant contributions over a 24-hour period, then the Half AEQ approach is invalid. In that situation, the target ventilation could indeed be lower during unoccupied periods, but would also need to be higher during occupied times to balance out the total.

These dynamics are recognized in other ventilation standards (e.g., Danish Building Regulations (Danish Enterprise and Construction Authority, 2010) (BR10) and UK Building Regulations (Part F) (Her Majesty's Government, 2010)) which require higher ventilation rates during occupied periods than we used in our analysis – roughly 0.5 ACH. To be consistent with these approaches, the occupant portion of the 62.2 requirement could be normalized to occupied hours. For example, given 16-hours of daily occupancy, the 3.5 L/s/person requirement in 62.2 would become 5.25 L/s/person during occupied hours (and 0 during unoccupied times).

The ratio of contributions between occupant activities and background building emissions are largely unknown, and it is variable between different pollutants. For example, we expect that formaldehyde is largely contributed to the indoor air by building materials and furnishings with very little occupant-related emissions. On the other hand, particles have some non-occupant related sources (outside air) as well as episodic indoor sources that are largely driven by human activity (cooking and other combustion-related activities).

We explore some of these dynamics by presenting two cases. For our initial cases, we used the same target ventilation rate during all minutes of the year (equal to Q_{tot} from 62.2-2016) in our relative exposure calculations. We refer to these as 'Full AEQ' cases. We then halved the target rate used in exposure calculations during unoccupied periods (corresponding to halving the sources of pollutants during unoccupied times[1]), and we refer to these cases as 'Half AEQ'. Note that this is a merely illustrative example and further research is required to determine a range of appropriate values for the changes in pollutant sources between occupied and unoccupied times.

Figure 7 illustrates relative exposure in the occupancy control for a Baltimore home with Full AEQ and Half AEQ target ventilation rates used in relative exposure calculations. The relative dose for this same control and time period is shown in Figure 8. The unoccupied period (highlighted in grey) is fixed, but the Half AEQ case rises at half the rate during the unoccupied period and the peak is less than half the Full AEQ (1.5 vs. 2.7). Because the peak exposure is so much lower in the half AEQ case the recovery time needed to reduce integrated relative exposure below one is also reduced. In this example case, the recovery time for the Half AEQ case was 2 hours and 45 minutes, compared to 6 hours and 20 minutes for the Full AEQ. Note, this shorter recovery period is very similar to that required for our 2-hour flush out strategy (see Section 4.2.1). The shorter recovery period reduces the total airflow required to maintain integrated relative exposure below one, which reduces annual air exchange and shifts ventilation to earlier time periods with warmer temperatures (e.g., early vs. late evening).

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[1] This approach is close to setting the target ventilation rate during unoccupied periods to solely the floor area part of the 62.2 calculation (i.e., 0.15 L/s per m^2 floor area (0.03 cfm per ft^2)). In some cases, this works out to roughly one-half of the total requirement.

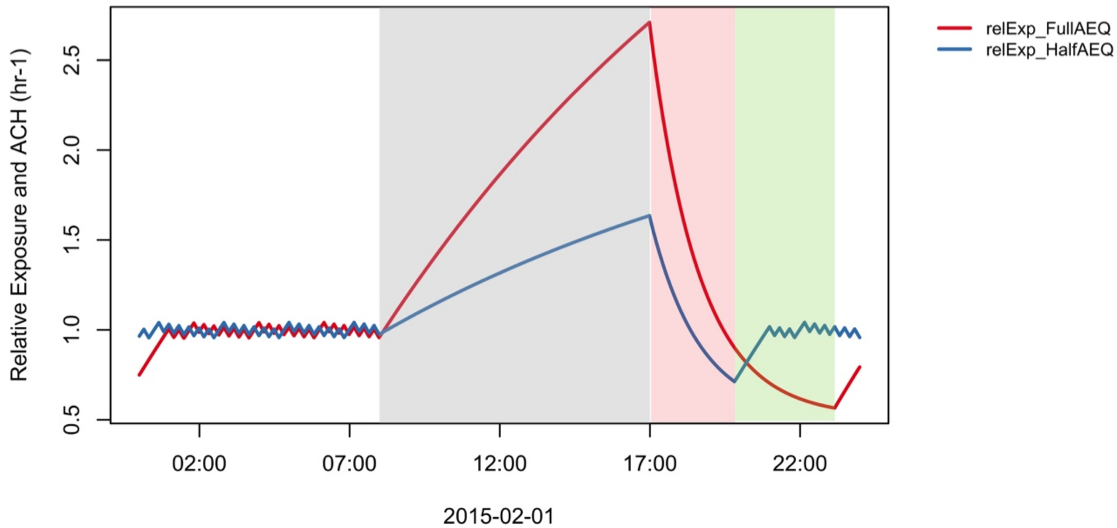

Figure 7 Relative exposure. Time series plot illustrating the Occupancy control function with Full AEQ (red line) and Half AEQ (blue line) ventilation targets in Baltimore home. Unoccupied period highlighted in grey, Half AEQ recovery period in pink, and Full AEQ recovery period in green.

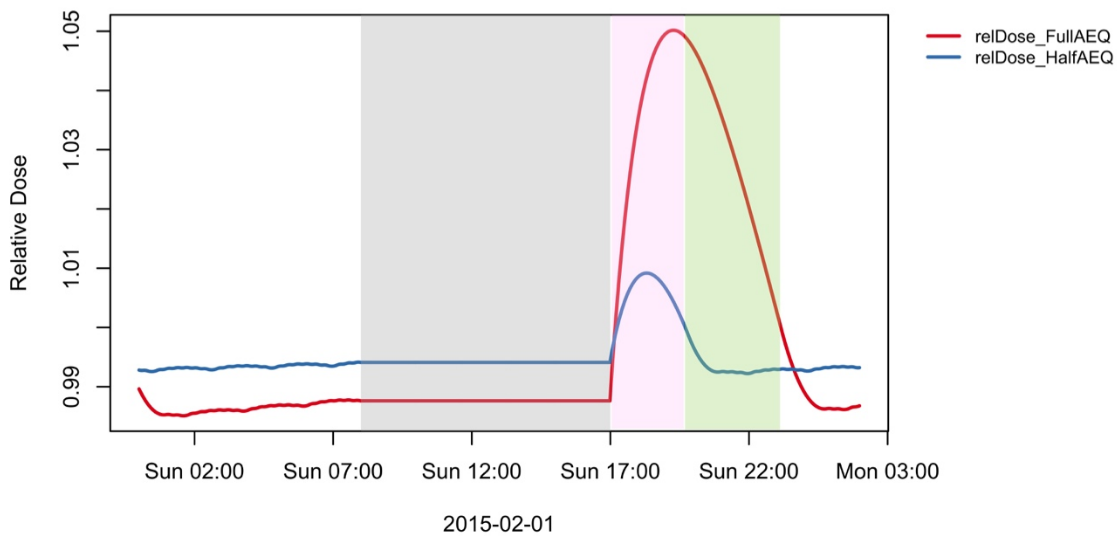

Figure 8 Relative dose. Time series plot illustrating the Occupancy control function with Full AEQ (red line) and Half AEQ (blue line) ventilation targets in Baltimore home. Unoccupied period highlighted in grey, Half AEQ recovery period in pink, and Full AEQ recovery period in green.

4 Results

Annual ventilation-related energy savings (%) are compared for each occupancy pattern, case (i.e., Full AEQ, Half AEQ and Balanced Fans), control type and baseline (NULL vs. continuous fan) in Table 7. These results are plotted for Auxiliary Fan SVC (Figure 9), Occupancy SVC (Figure 10), AuxFan + Occupancy SVC (Figure 11) and a comparison across the three SVC for just the 1st shift occupancy pattern (Figure 12).

The annual air exchange rates and relative exposure values are summarized in Table 6. All median values reported below are aggregated across the 15 DOE climate zones and sometimes across occupancy pattern. So, for example, the annual average relative exposure is calculated for each case, and we report the median of these values across all CZ and occupancy patterns. Detailed annual data summaries are presented for each individual case for Full AEQ (Table 16), Half AEQ (Table 17) and Balanced (Table 18) in the Appendix. In all cases, energy performance is characterized by the ventilation energy savings (%) relative to the matched baseline case (see Table 1). Total HVAC kWh savings are also reported in some cases.

Sub-sections below discuss the results for Full AEQ (Section 4.2), the pre-occupancy flush out (Section 4.2.1), half AEQ (Section 4.3) and balanced fan (Section 4.5) cases. Energy end-use savings are pictured in Section 4.4. The energy savings of the controls depended greatly on the selected baseline scenario—either NULL control or continuous IAQ fan. We present results using both of these two baseline assumptions in parallel.

Energy performance in the control cases was determined by the change in total house air exchange (greater reduction leads to greater savings), as well as by the outdoor temperatures during that air exchange (reduced air exchange during times with greater indoor-outdoor temperature differences leads to greater savings). So, strategies that had greater reductions in air exchange (e.g., Half AEQ assumption and pre-occupancy flush out) had greater energy savings. Similarly, some SVC reduced ventilation rates during periods of higher indoor-outdoor temperature differences (e.g., Occupancy SVC for the 3rd shift) and had higher savings, while others reduced ventilation during mild times of day and had minimal effect (e.g., Occupancy SVC for the 1st shift). Consistent with this, absolute energy savings scaled positively with climate severity, as the benefit of reducing ventilation rates increased with greater temperature differences. Percentage ventilation energy savings remained fairly stable across climate zones.

The combined Auxiliary Fan + Occupancy control had the greatest energy savings, with total savings that were generally roughly equivalent to the sum of the savings from the two individual controllers. In most scenarios, the Auxiliary Fan SVC saved more energy than the occupancy SVC; the only exception was for the occupancy pattern with 12-hour daily absence and substantial weekend absences. The 3rd shift occupancy pattern showed greater energy savings for all occupancy cases, because the period of reduced ventilation (nighttime for the 3rd shift) was also a period of greater indoor-outdoor temperature differences, which leads to heating savings. Energy savings for occupancy controls increased as unoccupied times increased. We similarly expect that auxiliary fan savings will increase with greater fan usage. The half AEQ emissions assumption during unoccupied periods had the highest energy savings, roughly double those with the Full AEQ emission assumption. Use of the NULL control baseline showed greater energy savings than the continuous fan baseline in nearly all cases and scenarios, with the exception of some cooling dominated locations. Balanced fans had higher percentage savings than exhaust fans, but they also had higher baseline ventilation energy use due to higher air exchange rates.

Case	Fan Type	AEQ Type	Air Exchange (hr^{-1})	Relative Exposure
No IAQ fan	NA	NA	0.102	4.959
Continuous IAQ fan	Exhaust	NA	0.340	1.005
	Balanced	NA	0.358	0.999
NULL IAQ Controller[2]	Exhaust	NA	0.352	0.995
Aux Fan	Exhaust	NA	0.325	0.988
	Balanced	NA	0.328	0.991
Occupancy	Exhaust	Full	0.326	1.001
	Exhaust	Half	0.298	0.996
	Balanced	Full	0.328	1.007
Aux Fan + Occupancy	Exhaust	Full	0.299	0.993
	Exhaust	Half	0.270	0.990
	Balanced	Full	0.299	0.997

Table 6 Median values for annual average air exchange rate and relative exposure for each control strategy, fan type and AEQ type.

[2] NULL Control is the baseline for Full AEQ performance assessments.

Occupancy Pattern	***Baseline***	***Case***	***Control Type***		
			Aux Fan	***Occupancy***	***Aux Fan + Occupancy***
1st Shift	NULL	Full AEQ	11.7	6.3	17.2
	Continuous		5.4	-0.2	11.1
	Continuous	Balanced	12.0	7.0	18.8
	NULL	Half AEQ	NA	17.4	29.0
	Continuous		NA	11.1	23.4
1st Shift Extended	NULL	Full AEQ	11.6	17.4	30.4
	Continuous		3.5	7.6	22.3
	Continuous	Balanced	11.0	15.5	31.0
	NULL	Half AEQ	NA	33.5	46.0
	Continuous		NA	26.1	40.2
3rd Shift	NULL	Full AEQ	11.5	9.4	19.7
	Continuous		5.6	2.9	13.6
	Continuous	Balanced	11.7	10.2	20.8
	NULL	Half AEQ	NA	20.5	31.9
	Continuous		NA	14.8	26.6

Table 7 Median ventilation annual energy savings (%) for each occupancy pattern, case, control type and baseline.

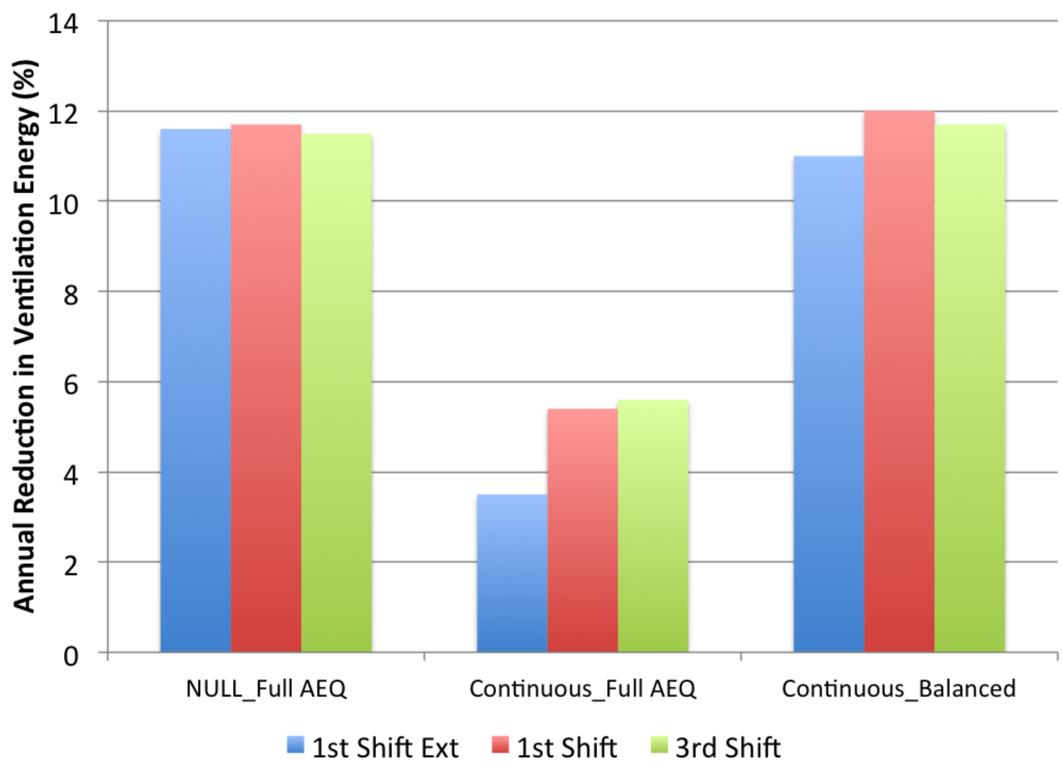

Figure 9 Auxiliary fan SVC, comparison of median ventilation energy savings for different baseline and fan types. First set of bars is the NULL control baseline cases, FULL AEQ emission assumptions. Etc.

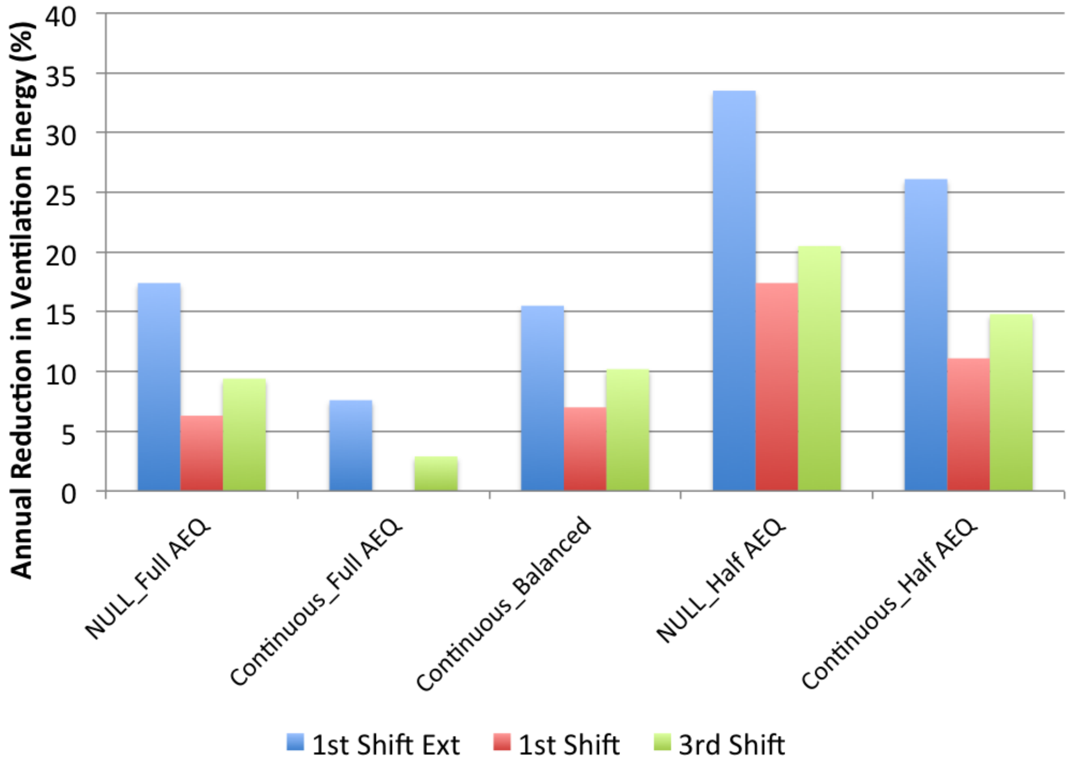

Figure 10 Occupancy SVC, comparison of ventilation energy savings for different baselines, fan types and unoccupied emission assumptions.

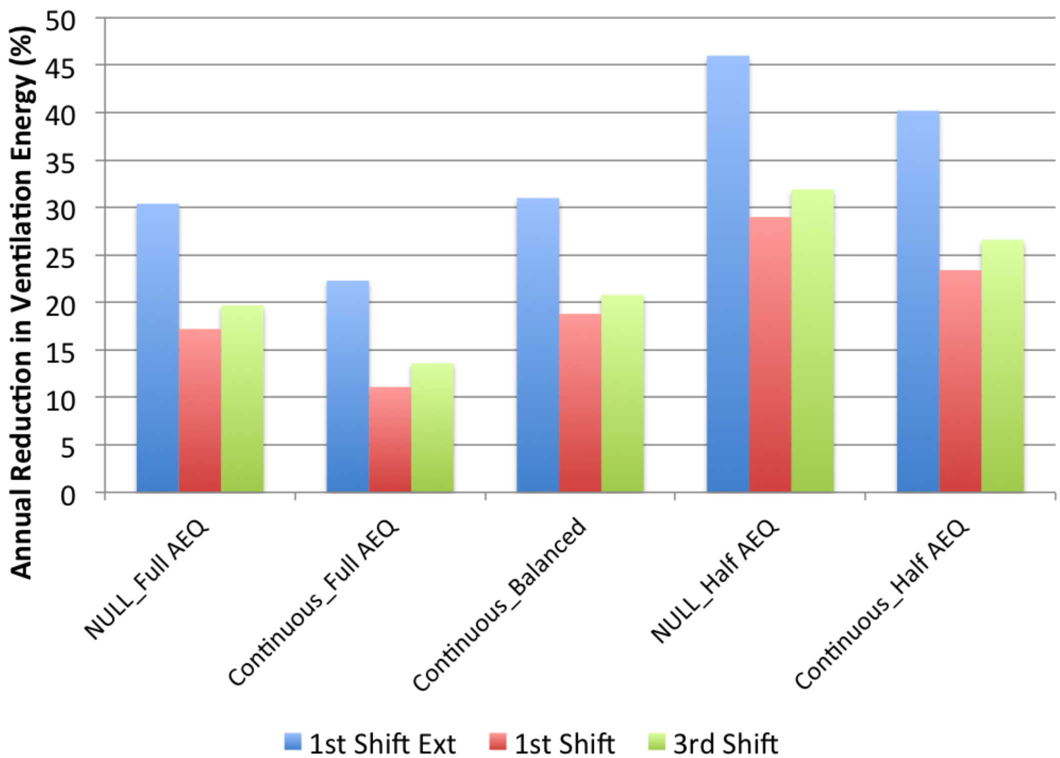

Figure 11 Auxiliary Fan + Occupancy SVC, comparison of ventilation energy savings for different baselines, fan types and unoccupied emission assumptions.

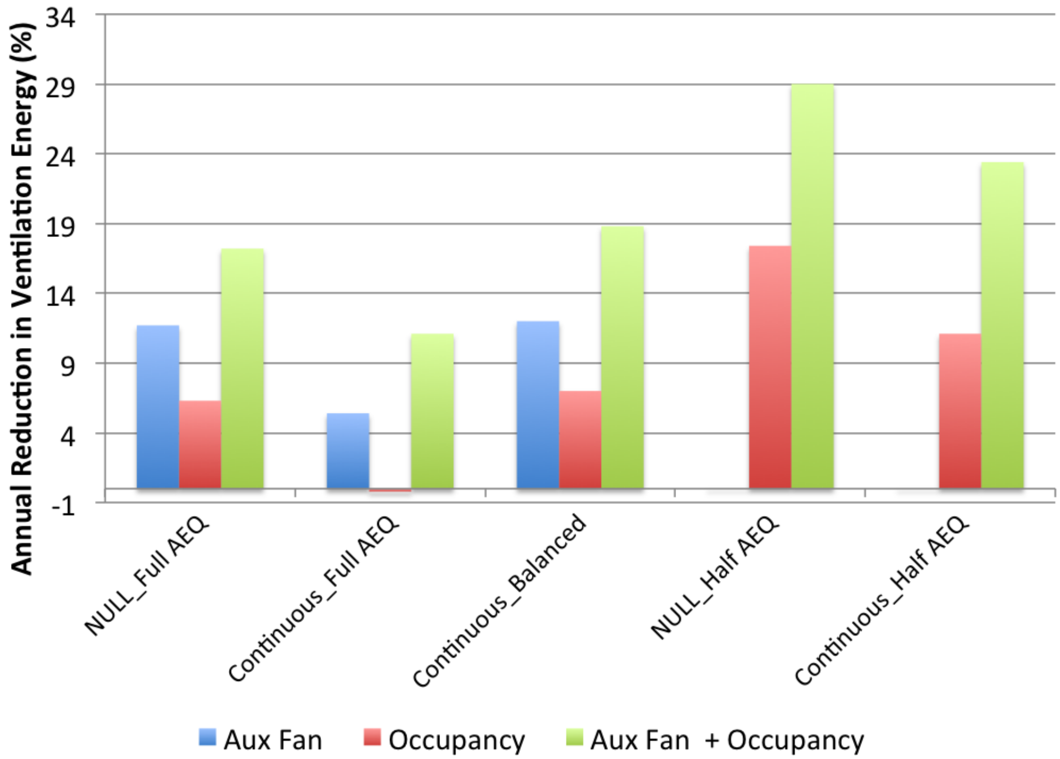

Figure 12 1st shift occupancy pattern, comparing ventilation energy savings across the three SVC strategies, for different baselines, fan types and unoccupied emission assumptions.

4.1 NULL Control vs. Continuous Fan Baselines

Relative to a continuous fan sized to 62.2-2016, use of the NULL control led to a median increase in house air exchange of 0.012 hr^{-1} (3.5% increase), going from a median of 0.340 to 0.352 hr^{-1}. The median annual average relative exposure in the continuous fan cases was 1.005 vs. 0.995 in the NULL control cases. The increase in energy use due to use of the NULL controller is shown across climate zones in Figure 13. Based on our findings varying the sizing of balanced ventilation fans (detailed in Section 4.5.1), we estimate that superposition of unbalanced fans and infiltration dominate the air exchange and energy impacts of the NULL controller. We believe that reducing relative exposure by 1% is a secondary effect. These effects ranged from essentially none in Miami to around an 1,100 kWh per year increase in Fairbanks, Alaska. Typical values in moderate U.S. climates were in the 300-400 kWh range. These reflect the penalty of simply using a IAQ controller to cycle on-off an over-sized fan (or any over-sized fan operated cyclically on a timer). If the continuous exhaust fan is used as the baseline, then the control cases would need to overcome these NULL control penalties in order to show any savings. Indeed, when using the simple exhaust as the baseline, there are some cases in which the energy penalty of using a controller exceeds the savings of the strategy. Annual HVAC energy use increased in these cases. This makes prediction of control performance based on first principles difficult, and it can make results difficult to interpret.

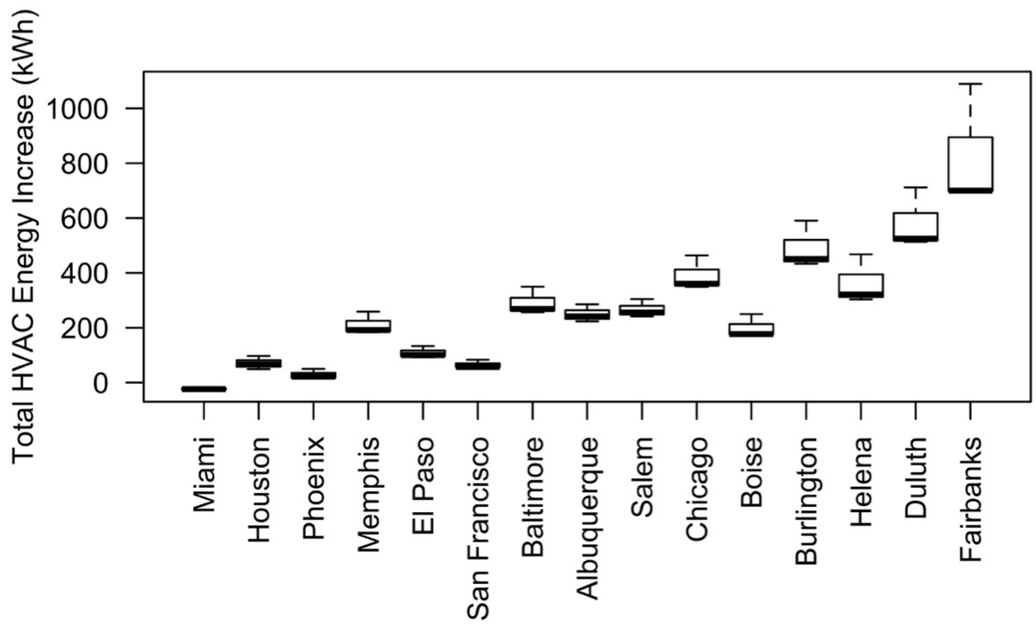

Figure 13 Annual energy use increases due to use of the NULL Controller, relative to a continuous fan baseline.

4.2 Full AEQ – Fixed Target Ventilation Rate Independent of Occupancy

For the Full AEQ simulations (which assume a fixed contaminant emission rate whether the home is occupied or not), median energy and percentage savings relative to the NULL control baseline are summarized for each control strategy and occupancy pattern in Table 8 (continuous fan baseline results in Table 9). Annual average air exchange rates and relative exposure are summarized in Table 6. Smart controls reduced annual average air exchange by between 7 and 15%, while maintaining equivalence with ASHRAE 62.2-2016 during occupied hours. The smart ventilation control energy savings estimates for each case are summarized by the percentage of ventilation energy saved (%) in Figure 14 (boxplot distributions for each control type) and Figure 16 (barplot of savings for each individual case) for the full AEQ ventilation targets using NULL control baseline. The same controls are compared with the continuous fan baseline in Figure 15 and Figure 17.

The baseline used for assessing ventilation energy savings made a substantial difference in the control performance. The Aux Fan and Occupancy controls were affected similarly by the choice of baseline, with the NULL control baseline showing roughly 60% more energy savings than with a continuous fan. The combined controls were less affected, with median increased savings of 27% for NULL vs. continuous fan baselines. The percentage savings estimates were stable when using the NULL baseline (see Figure 16), but they become much more erratic when using the continuous fan baseline (see Figure 17 for comparison). Mostly notably, more than half of the 1st shift Occupancy SVC cases actually increased ventilation energy relative to the continuous fan baseline (see Figure 17). These cases only showed savings relative to the NULL control baseline. This was the result of low reductions in the air exchange rate, combined with mild conditions during the reduced ventilation hours.

The total annual savings (kWh/year) are shown in Figure 18 and Figure 19 for NULL control baseline (organized by control strategy or occupancy pattern), with annual savings estimates ranging between roughly 100 and 2,700 kWh per year, representing between 5 and 40% of ventilation-related energy. The continuous fan baseline annual savings are shown in Figure 20 and Figure 21, with savings estimates ranging from roughly -150 to 1,690 kWh per year, representing between -5 and 40% ventilation energy savings. Annual Full AEQ results are also tabulated for each case in Appendix Table 16 (annual performance, energy, AER, relative dose and exposure) and Appendix Table 19 (annual savings kWh/yr).

As all SVC assessed in this work operate on a 24-hour period, the diurnal temperature pattern was important in determining the energy impacts of the strategies. In general, energy savings were the result of reduced ventilation rates in the control cases, but the savings varied further by the outside temperatures during the times of higher or lower ventilation. This effect drove the higher energy savings in the 3rd vs. 1st shift occupancy patterns—the time with reduced ventilation rates had higher indoor-outdoor temperature differences. To illustrate these effects, we calculated the distributions of indoor – outdoor temperature differences for a Baltimore home for the 1st and 3rd shift unoccupied and recovery periods (see Table 10). These are the periods of reduced ventilation and increased ventilation, respectively. During recovery periods, the temperature differences are nearly identical, with mean differences of 10.0 and 9.9°C for 1st and 3rd shifts. So, for Baltimore, it is not the higher ventilation period that affects energy performance, rather it's the unoccupied period of reduced ventilation. During unoccupied periods, we see a sharp distinction, with much higher average temperature differences during the 3rd shift unoccupied period (12.4 vs. 7.5°C). So, the benefit of reducing the ventilation rate is much greater for the 3rd shift pattern, which leads to higher average savings across all SVC.

Occupancy Pattern	*Annual Reduction in Ventilation Energy (%)*		
	Aux Fan	*Occupancy*	*Aux Fan + Occupancy*
1st	11.7	6.3	17.2
1stExt	11.6	17.4	30.4
3rd	11.5	9.4	19.7
	Annual HVAC Energy Savings (kWh)		
1st	384	181	497
1stExt	410	469	850
3rd	383	309	612

Table 8 Full AEQ, NULL control baseline. Median annual reductions in the ventilation energy and HVAC energy savings, by occupancy pattern and control type.

Occupancy Pattern	*Annual Reduction in Ventilation Energy (%)*		
	Aux Fan	*Occupancy*	*Aux Fan + Occupancy*
1st	5.4	-0.2	11.1
1stExt	3.5	7.6	22.3
3rd	5.6	2.9	13.6
	Annual HVAC Energy Savings (kWh)		
1st	142	-9	299
1stExt	88	248	580
3rd	142	64	389

Table 9 Full AEQ, continuous fan baseline. Median annual reductions in the ventilation energy and HVAC energy savings, by occupancy pattern and control type.

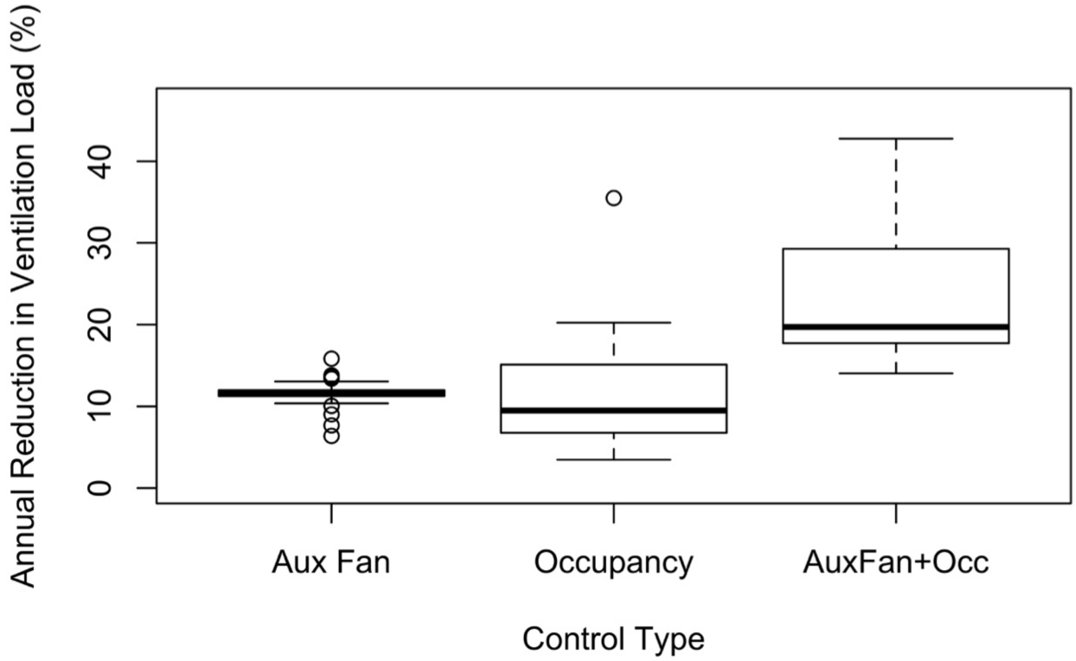

Figure 14 Full AEQ, NULL control baseline. Annual reductions in ventilation energy by control type, aggregated across climate zones and occupancy patterns.

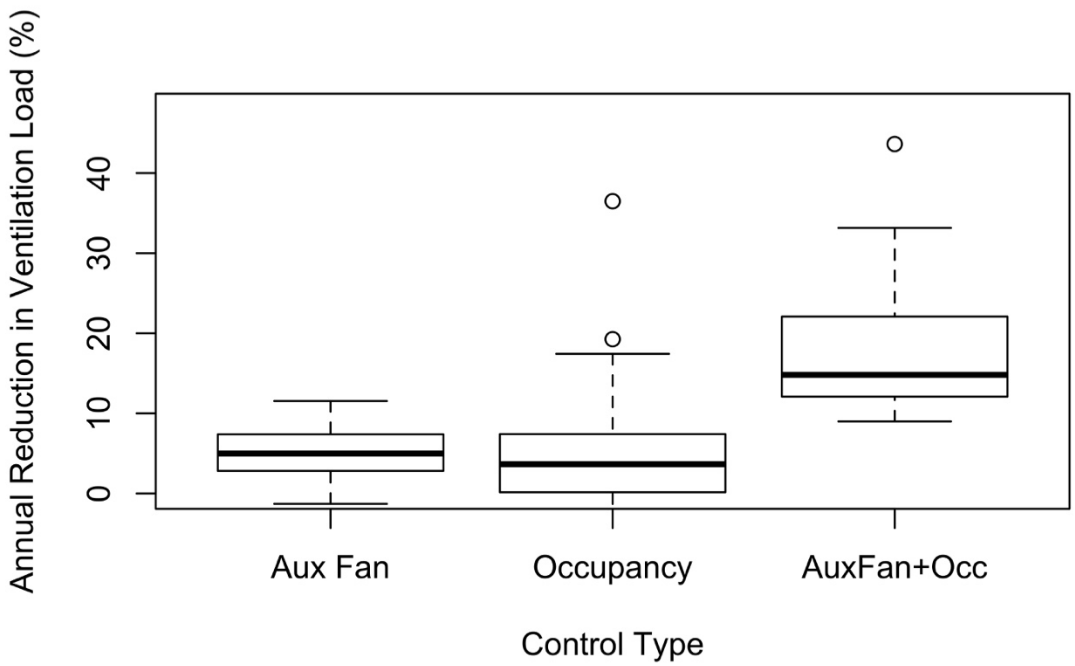

Figure 15 Full AEQ, continuous fan baseline. Annual reductions in ventilation energy by control type, aggregated across climate zones and occupancy patterns.

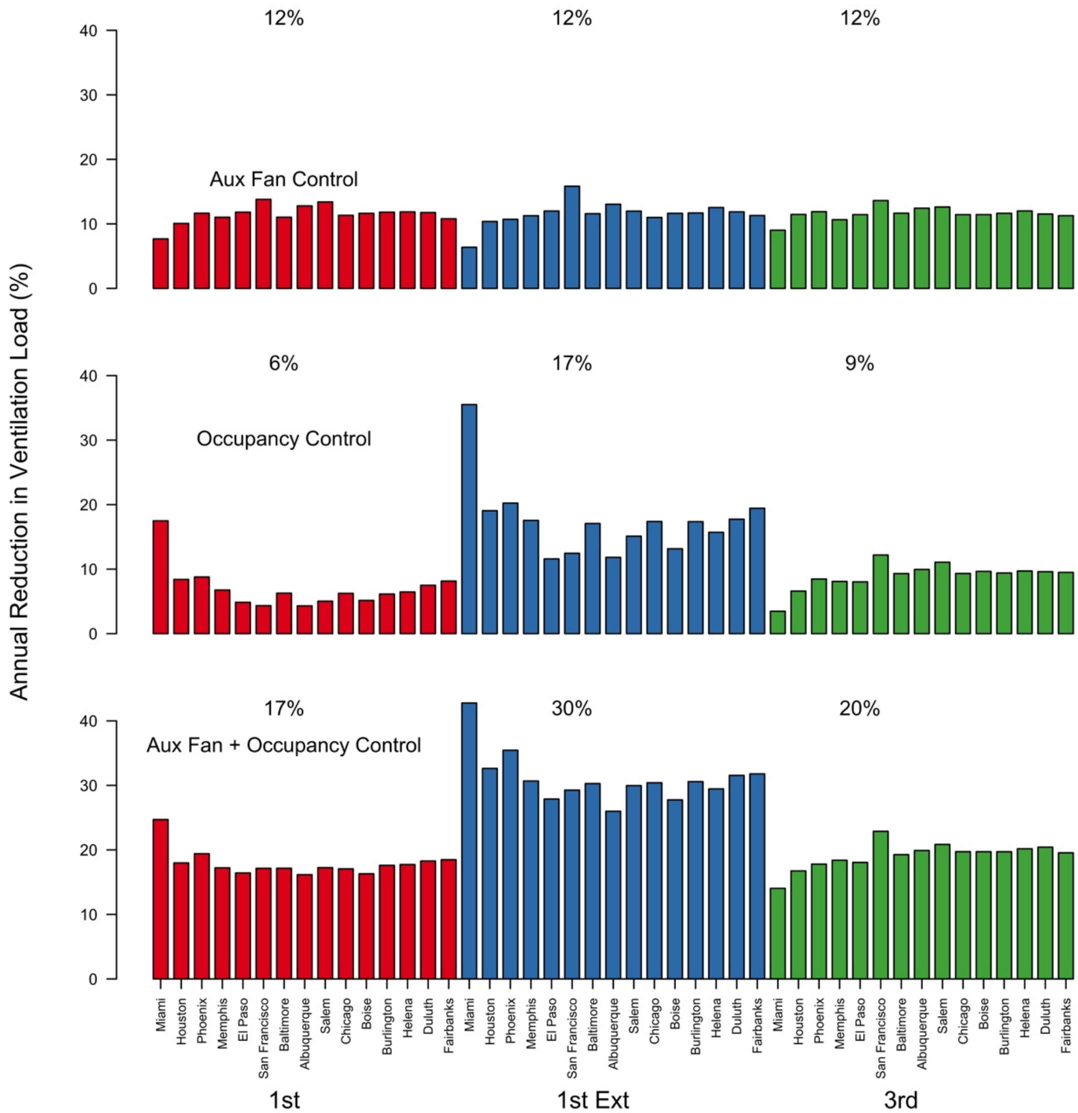

Figure 16 Full AEQ, NULL Control baseline. Annual percent reduction in the 62.2-2016 ventilation energy use for each climate zone, control type and occupancy pattern.

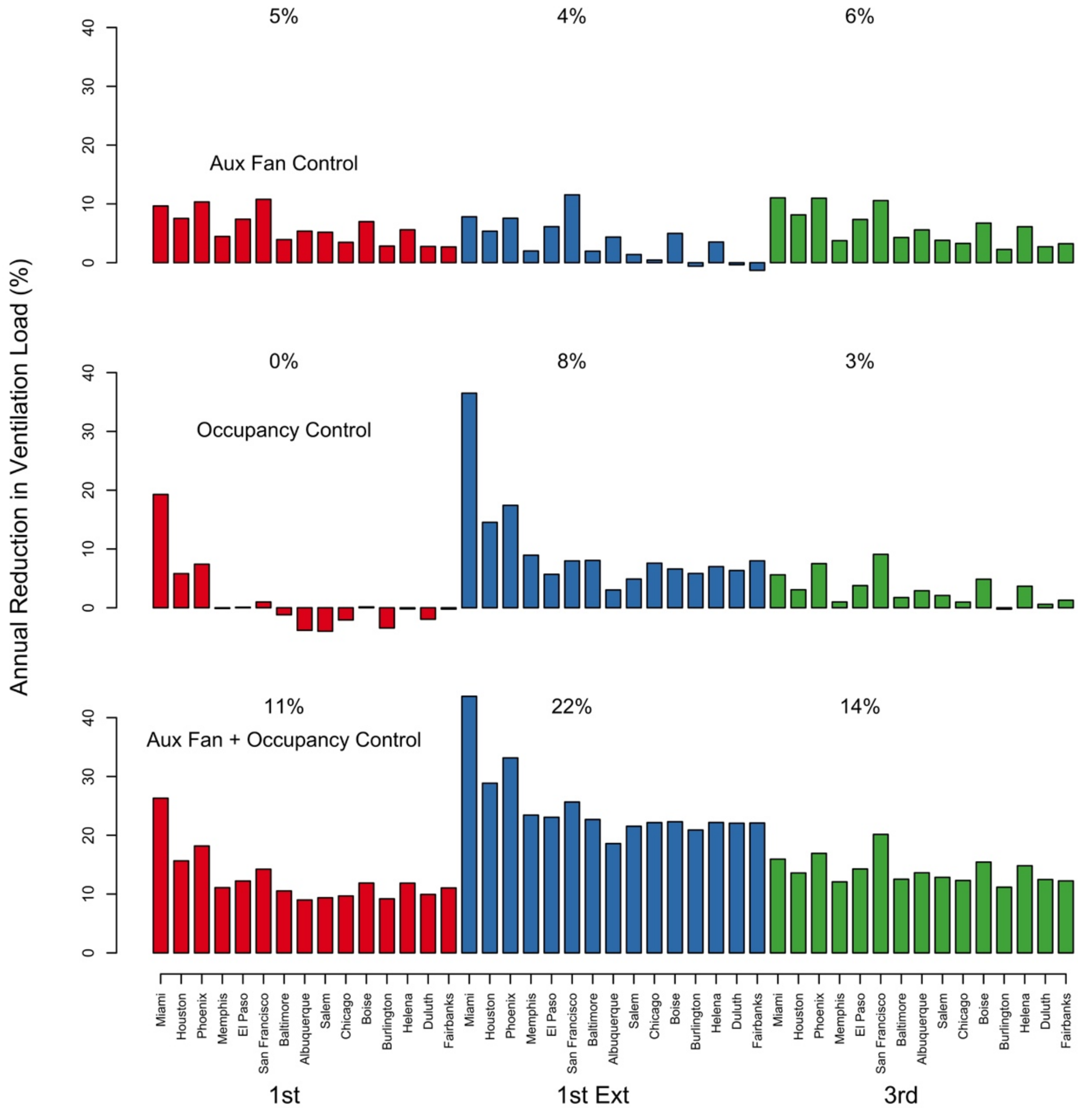

Figure 17 Full AEQ, continuous fan baseline. Annual percent reduction in the 62.2-2016 ventilation energy use for each climate zone, control type and occupancy pattern.

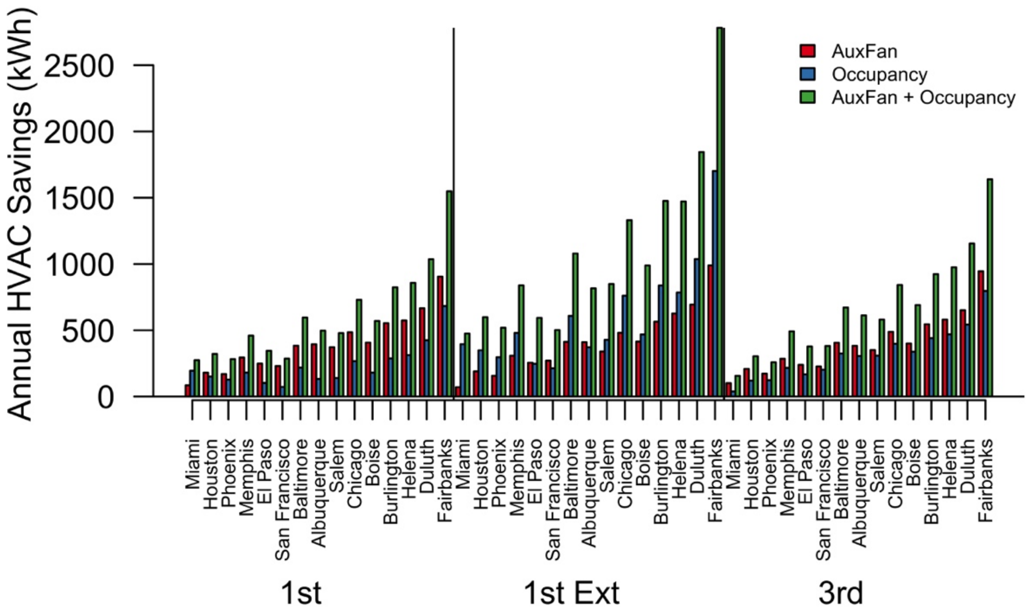

Figure 18 Full AEQ, NULL control baseline. Annual HVAC energy savings for each climate zone and occupancy schedule, by fan control type.

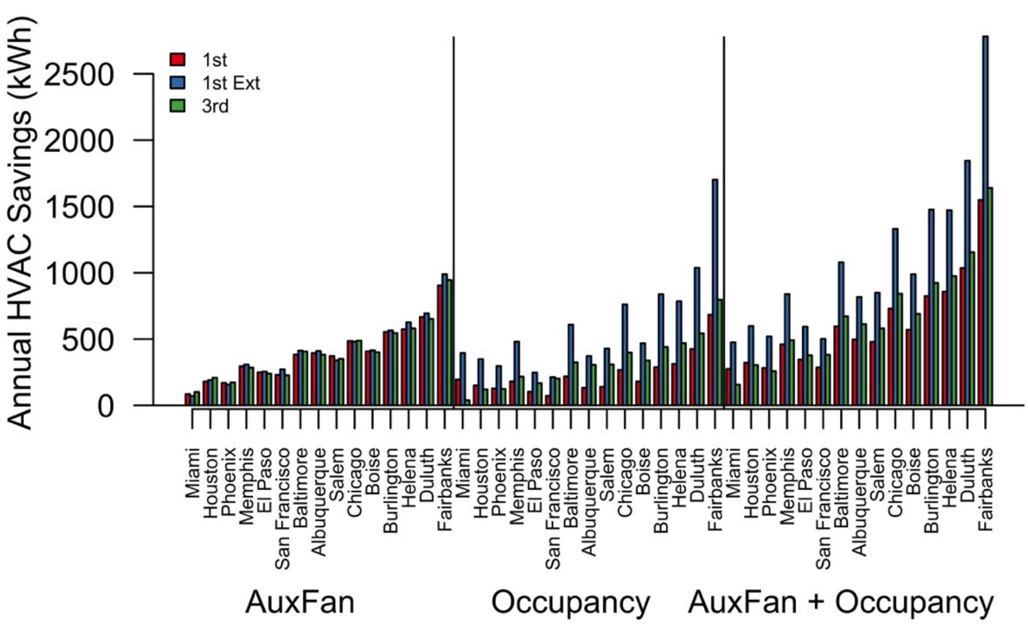

Figure 19 Full AEQ, NULL control baseline. Annual HVAC energy savings for each climate zone and fan control type, by occupancy schedule.

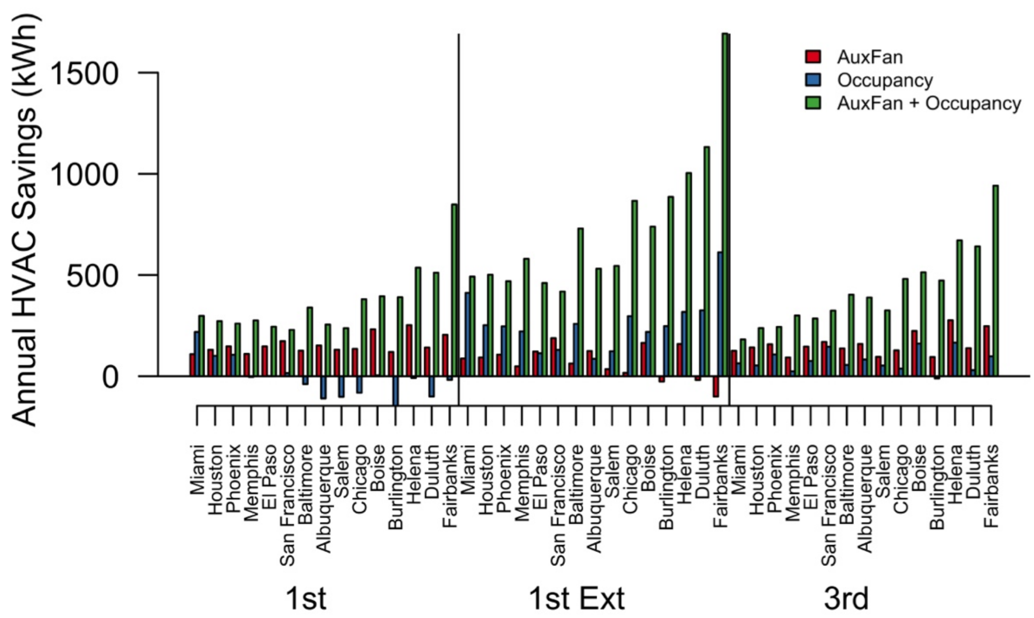

Figure 20 Full AEQ, continuous fan baseline. Annual HVAC energy savings for each climate zone and occupancy schedule, by fan control type.

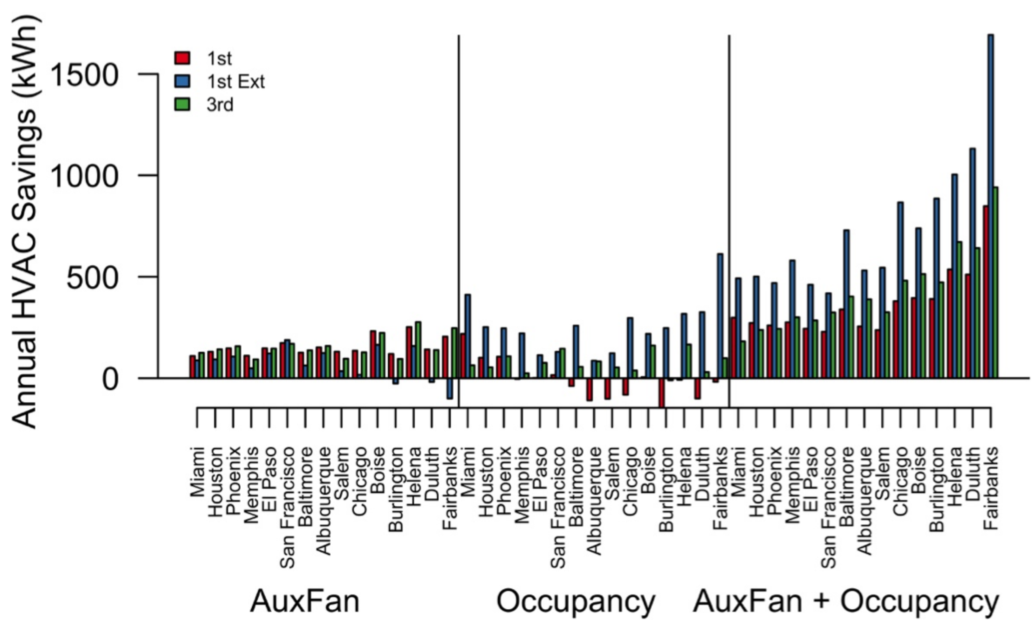

Figure 21 Full AEQ, continuous fan baseline. Annual HVAC energy savings for each climate zone and fan control type, by occupancy schedule.

Shift	Time Period	Indoor – Outdoor Temperature Difference (°C)					
		Min	25th	Median	Mean	75th	Max
1st	Recovery, 17:00 – 22:00	-8.3	2.5	10.2	10.0	16.2	34.3
3rd	Recovery, 06:00 – 11:00	-8.9	2.5	9.2	9.9	16.8	35.9
1st	Unoccupied, 08:00 – 16:00	-9.9	-0.3	6.9	7.5	14.2	35.5
3rd	Unoccupied, 21:00 – 05:00	-5.2	5.5	12.0	12.4	18.4	36.2

Table 10 Distribution of indoor - outdoor temperature differences for recovery and unoccupied time periods in Baltimore.

The controllers were programmed to limit relative exposure to at most 5, but in practice, the peak exposure never exceeded 3.5 in any control simulation. A pre-ventilation strategy based on anticipated occupancy could be used to drastically reduce this exposure peak, an effect we explore in Section 4.2.1.

Table 11 shows the reductions in IAQ fan airflow in the control cases relative to the airflow for the continuous baseline fan (NULL control baseline is not considered here). This does not include infiltration or auxiliary fan airflows, rather it indicates just IAQ fan airflow rate and runtime. So, these reductions do not translate directly to reductions in house air exchange, due to the superposition effects discussed in Section 1.1.2. For example, based on annual average house air exchange rates in Table 6, the AuxFan + Occupancy controller only reduced house AER by 14% on average, which is consistently less than the IAQ fan flow reductions of 19 to 34%. In general, greater reductions in total airflow lead to greater energy savings for the controller. The reduction in fan airflow for the control cases was similar across climate zones, and was entirely dependent on the amount of auxiliary fan use and the amount of occupied vs. unoccupied time. As expected, the airflow through the IAQ fan decreased with greater unoccupied time, and reductions in IAQ fan airflow are greatest for the AuxFan + Occupancy controller. The 9% reduction for the Occupancy 1st and 3rd shift cases is perfectly in alignment with estimates of potential for demand controlled ventilation from (Mortensen et al., 2011b).

Occupancy Pattern	Control	IAQ Fan Flow Reduction (hr^{-1})	IAQ Fan Flow Reduction (%)
1st	Aux Fan	0.029	10%
1stExt	Aux Fan	0.028	10%
3rd	Aux Fan	0.029	10%
1st	Occupancy	0.027	9%
1stExt	Occupancy	0.060	22%
3rd	Occupancy	0.026	9%
1st	Aux Fan + Occupancy	0.055	20%
1stExt	Aux Fan + Occupancy	0.094	34%
3rd	Aux Fan + Occupancy	0.055	19%

Table 11 Full AEQ. Median reductions in the IAQ fan annual average airflow rate relative to the baseline continuous fan, by smart control type and occupancy pattern. Ignores infiltration and other sources of house air exchange.

4.2.1 Pre-Occupancy Flush Out

We tested a control approach for the Occupancy smart control that included a pre-occupancy flush out period. This was done only for the 1st shift occupancy pattern only, using only the NULL control baseline with exhaust fans. In these cases, rather than beginning the recovery period when occupants return home, the controller was able to predict their return and flush out the house prior to being occupied. We tested both a one- and two-hour flush out period. Both of these periods were effective at saving energy and reducing occupant peak exposure. Energy is saved because the pre-occupancy flush out reduces the total airflow required for the recovery period, resulting in a net-reduction in air exchange. In addition, for the first shift occupancy pattern in heating climates, the flush out shifts the recovery ventilation airflow to warmer times of day (late afternoon vs. early evening), with predictable heating energy benefits (and cooling energy penalties). The required higher ventilation is determined first by the high relative exposure that occurs when occupants return home, but this also drives the relative dose well above one. Relative exposure is brought below one quite quickly by the over-sized fan, but relative dose responds more slowly, and this effect dominates the total recovery time required.

For the 1st shift occupancy pattern, the annual HVAC energy savings are plotted in Figure 22 for the one- and two-hour pre-occupancy flush out periods for each climate zone. These savings estimates are in addition to the basic Occupancy SVC savings with no pre-occupancy flush out. Example daily plots of relative exposure (Figure 23) and relative dose (Figure 24) are provided to illustrate why the pre-occupancy flush out is effective.

Total energy savings varies from a slight usage increase in Miami up to over 400 kWh per year in Alaska. Median energy savings were 185 and 199 for the one- and two-hour flush outs, respectively. These energy savings more than double the 181 kWh per year median savings achieved by the Occupancy control without the pre-occupancy flush out (see Table 8). While on average, the two-hour flush out saved slightly more energy, this varied by climate zone.

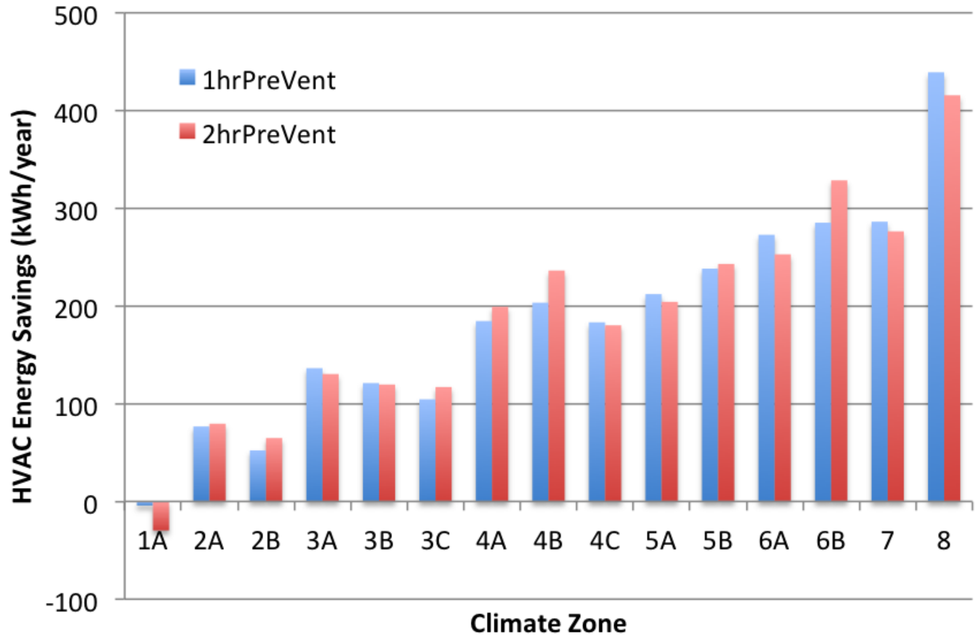

Figure 22 Annual HVAC energy savings for pre-occupant flush out periods of one- and two-hours, relative to the occupancy control with no pre-occupancy flush out. 1st shift example home in Chicago.

As is illustrated in Figure 23, the pre-occupancy flush out drastically reduces the occupant peak exposure and the duration of the high airflow recovery period. In all cases, the maximum exposure for the day occurs the minute occupants return home (17:00) (where the relative exposure line intersects with the right-side of the grey unoccupied period). The exposure at this time goes from 2.7 down to 1.6 for the one-hour flush out and 1.1 for the two-hour flush out period. This impacts the relative dose in the period immediately after the occupants return home, which is clearly illustrated in Figure 24. The two-hour pre-occupancy flush out has the shortest recovery period with the lowest total airflow (2-hour flush out plus 13-minutes after occupants return home), as the controller just begins cycling the fan normally almost immediately after occupancy. The one-hour pre-occupancy flush out has a recovery period of 2-hours and 40-minutes after occupants return home (one-hour prior to their return, 3 hours and 40-minutes total). Somewhat more total airflow is required in this case. In contrast, the version of the control with no pre-occupancy flush out has a recovery period lasting 6-hours and 12-minutes (all occurring after occupants return home).

Turning the fan off for nine hours reduces house airflow by 38%, but including the higher ventilation recovery period reduces this to only a 12% daily reduction. The effects of the recovery period were reduced by pre-occupancy flush out. A one-hour pre-occupancy flush out allows a daily airflow reduction of 22% and a two-hour flush results in a reduction in daily airflow of 28%.

The higher integrated relative exposure resulting from no pre-occupancy flush out drives most of the recovery period. For the no flush out control, the relative exposure is controlled to below one in only 2-hours and 28-minutes, but relative exposure must be maintained below one to compensate for the time spent above one. This necessitates an additional 3-hours and 44-minutes of higher ventilation rates (60% of the recovery period).

A concern 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 such that the flush out does not occur at the correct time. However the results show that a one-hour flush out is roughly equivalent in energy performance as the two-hour flush out. This means that a robust approach of having the flush out start earlier and last for two hours rather than trying to accurately predict the correct single hour for flush out has an insignificant energy penalty. This means that a system that works on a schedule that is manually entered by the occupants might be an acceptable control approach. Furthermore, starting the flush out earlier than necessary would benefit from the warmer outside conditions during the afternoon.

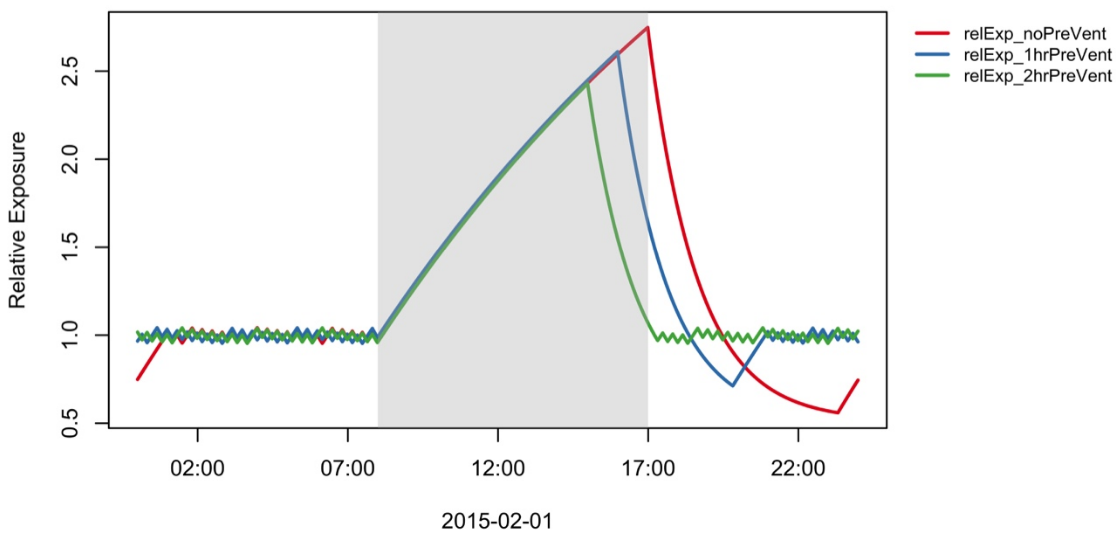

Figure 23 Relative exposure with no, one- and two-hour pre-occupancy flush out periods. Unoccupied period highlighted in light grey.

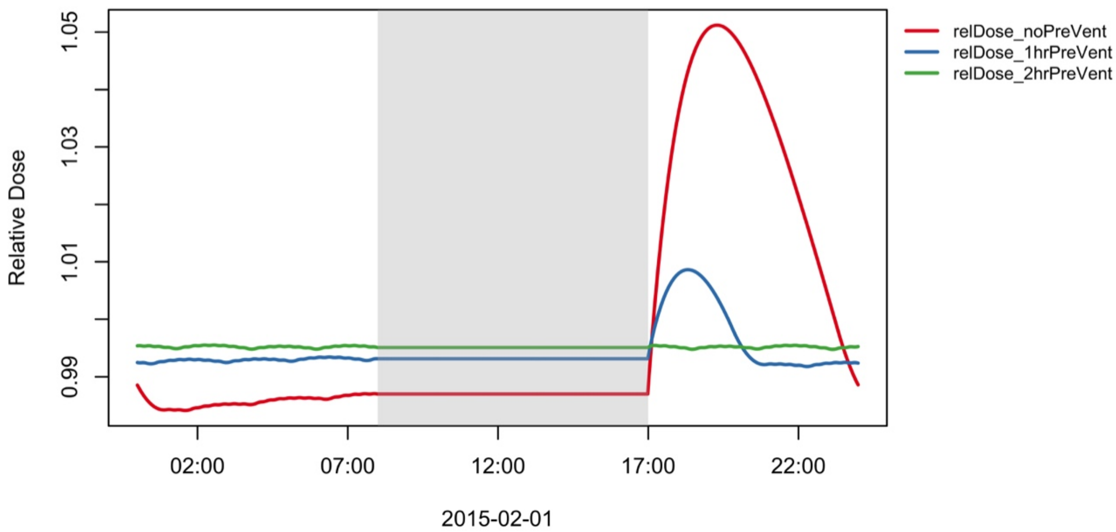

Figure 24 Relative dose with no, one- and two-hour pre-occupancy flush out periods. This is simply a control parameter for ensuring that 24-hour integrated relative exposure is less than one. Unoccupied period highlighted in light grey. 1st shift example home in Chicago.

Although it would be possible to precisely optimize pre-occupancy flush (depending on fan over-sizing, house size, natural infiltration, and unoccupied time period) to bring the relative exposure value to exactly one the minute occupants returned, the energy savings from Figure 22 suggest that the value of achieving this optimum is low. This implies that control design does not need to be concerned about perfect prediction of occupancy patterns, and that being within an hour of the correct time is sufficient.

4.3 Half AEQ – Target Ventilation Rate Halved During Unoccupied Times

Relative to the Full AEQ cases in Section 4.2, Half AEQ simulations assumed the target ventilation rate was halved during unoccupied time periods, which is equivalent to cutting the generic pollutant emission rate in half during unoccupied times. This change reduced the ventilation required for the recovery period, which reduced total airflow and saved energy. Compared with the default Full AEQ assumption, energy savings for occupancy-based controls increased by roughly a factor of two.

Median annual average air exchange rates and relative dose are summarized for each control in Table 6. Smart controls reduced annual average air exchange rates by between 7 and 23%, while maintaining equivalence with ASHRAE 62.2-2016 during occupied periods. Median annual HVAC energy savings and percent savings are provided for each control type and occupancy pattern in Table 12 for the NULL control baseline and in Table 13 for continuous fan baseline. The median absolute energy savings (kWh/year) are compared for Full and Half AEQ cases in Figure 25 (NULL control) and Figure 26 (continuous fan baseline). The change in kWh savings from Full to Half AEQ was similar with either baseline type, and median increases in savings ranged between 300-500 kWh.

The smart ventilation control energy savings estimates are summarized for each case by the percentage of ventilation energy saved (%) in Figure 27 and Figure 28 for the Half AEQ ventilation targets (NULL control and continuous fan baselines, respectively). The total annual savings (kWh/year) are shown in Figure 29 and Figure 30 (NULL control baseline) organized by occupancy pattern or smart control (see for Figure 31 and Figure 32 for continuous fan baseline figures). Savings varied from around 170 to 3,000 kWh, corresponding to roughly 10 to 50% reductions in ventilation-related energy use. Annual Half AEQ results are also tabulated for each case in Appendix Table 17 (annual performance, energy, AER, relative dose and exposure) and Appendix Table 20 (annual savings kWh/yr).

Occupancy Pattern	*Annual Reduction in Ventilation Energy (%)*		
	Aux Fan	*Occupancy*	*Aux Fan + Occupancy*
1st	11.7	17.4	29.0
1stExt	11.6	33.5	46.0
3rd	11.5	20.5	31.9
	Annual HVAC Energy Savings (kWh)		
1st	384	494	847
1stExt	410	936	1359
3rd	383	690	1076

Table 12 Half AEQ, NULL control baseline. Annual reduction in ventilation energy and HVAC energy savings, for each control type and occupancy pattern.

Occupancy Pattern	*Annual Reduction in Ventilation Energy (%)*		
	Aux Fan	*Occupancy*	*Aux Fan + Occupancy*
1st	5.4	11.1	23.4
1stExt	3.5	26.1	40.2
3rd	5.6	14.8	26.6
	Annual HVAC Energy Savings (kWh)		
1st	142	304	606
1stExt	88	660	1074
3rd	142	445	841

Table 13 Half AEQ, continuous fan baseline. Annual reduction in ventilation energy and HVAC energy savings, for each control type and occupancy pattern.

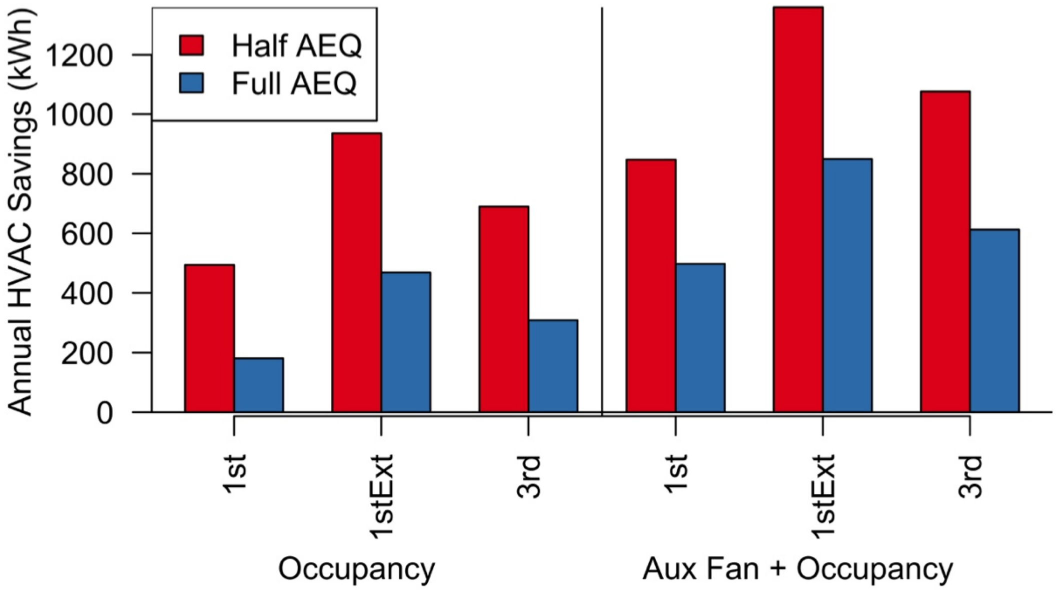

Figure 25 Half AEQ, NULL control baseline. Comparison of median ventilation energy savings, full versus half AEQ targets.

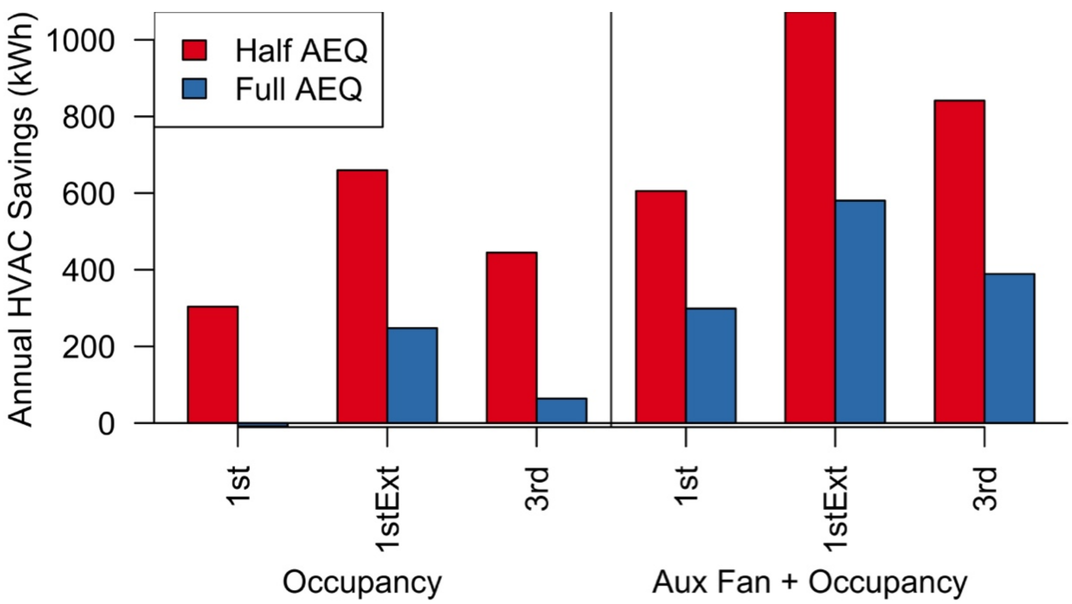

Figure 26 Half AEQ, continuous fan baseline. Comparison of median ventilation energy savings, full versus half AEQ targets.

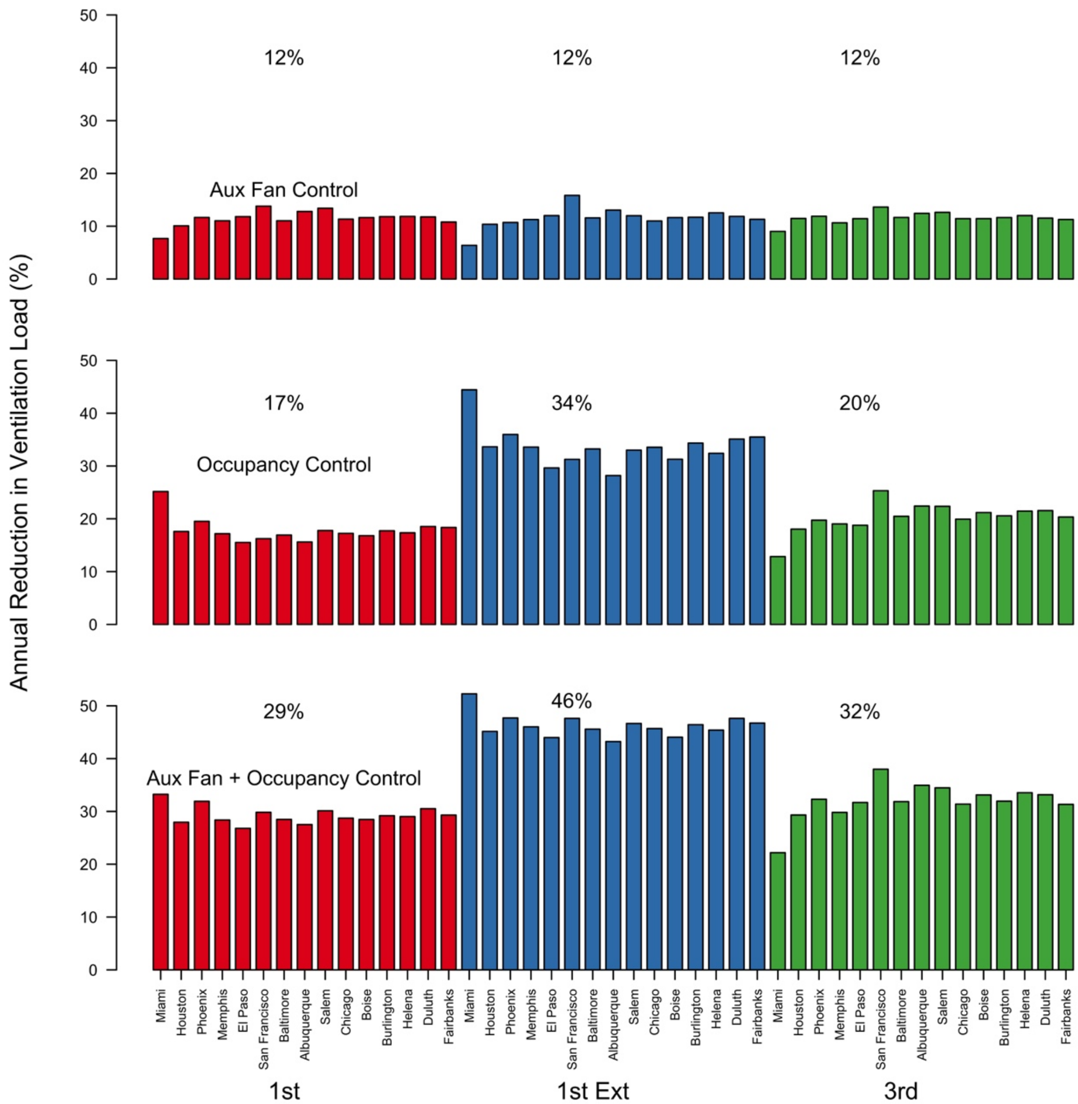

Figure 27 Half AEQ, NULL control baseline. Annual percent reduction in the 62.2-2016 ventilation energy use for each climate zone, control type and occupancy pattern. ***Note: the Aux Fan control is not affected by the half AEQ target during unoccupied periods.***

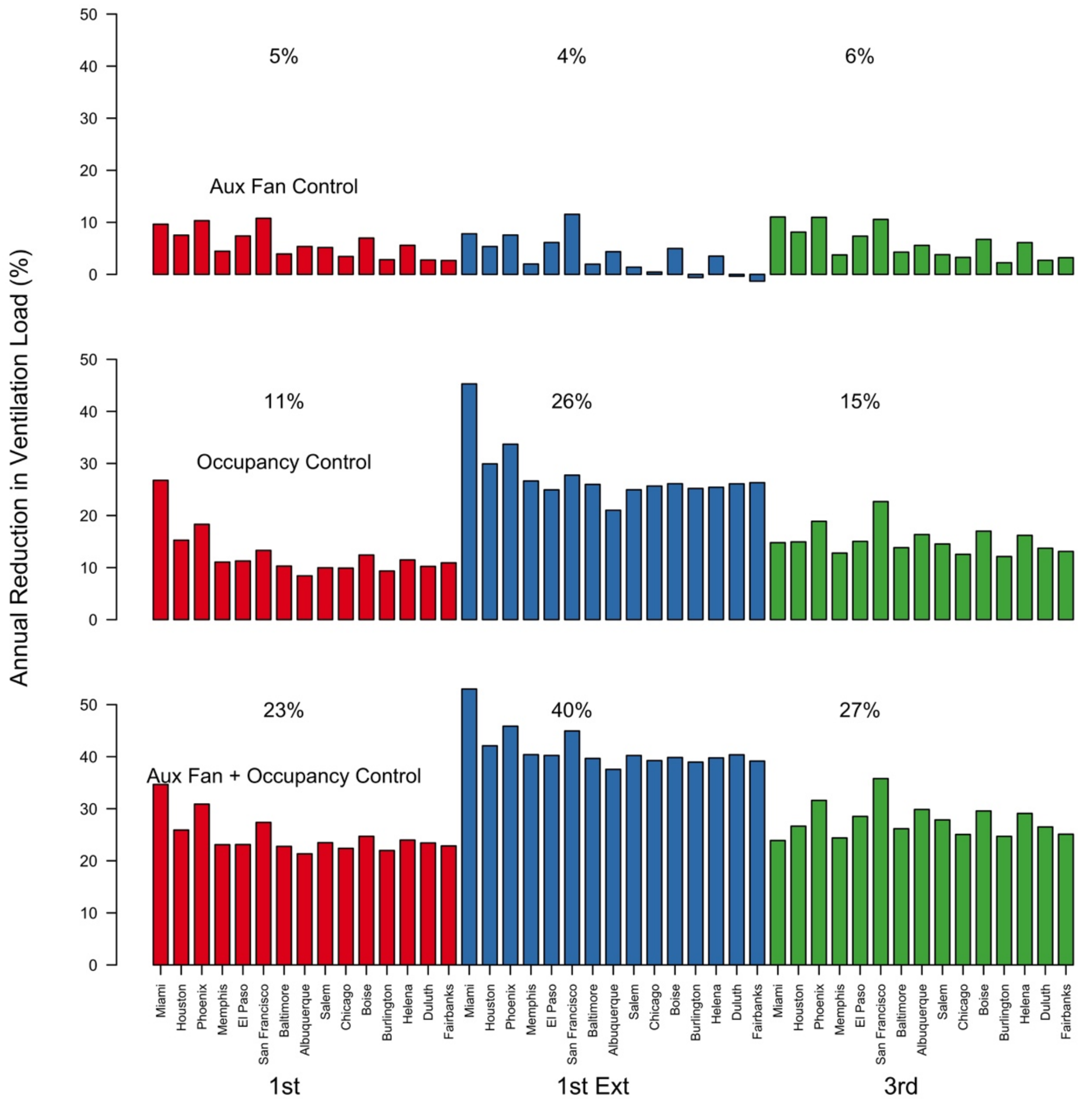

Figure 28 Half AEQ, continuous fan baseline. Annual percent reduction in the 62.2-2016 ventilation energy use for each climate zone, control type and occupancy pattern. ***Note: the half AEQ target does not affect the Aux Fan control during unoccupied periods.***

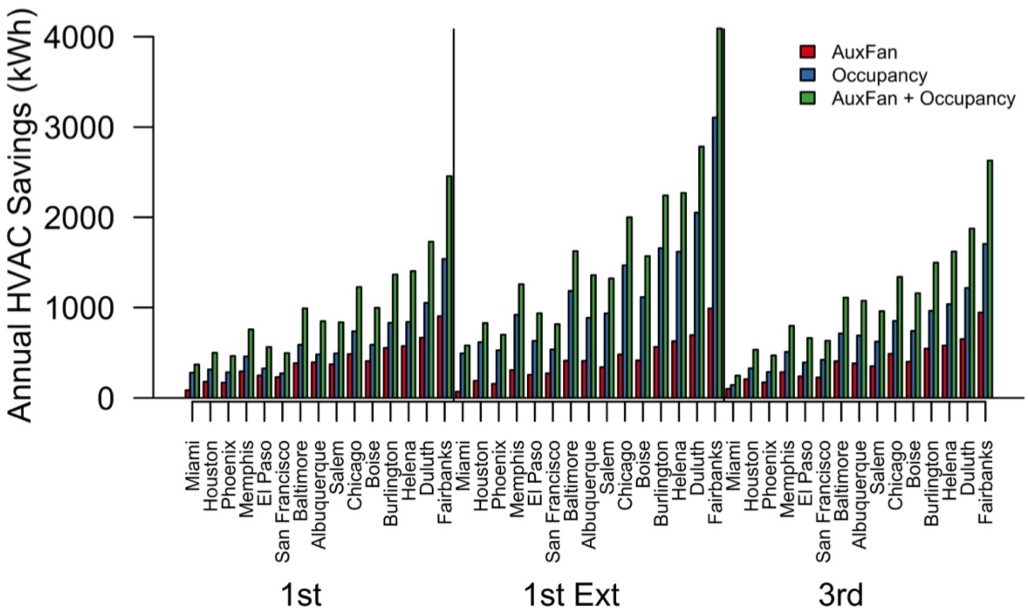

Figure 29 Half AEQ, NULL control baseline. Annual HVAC energy savings for each climate zone and occupancy schedule, by fan control type.

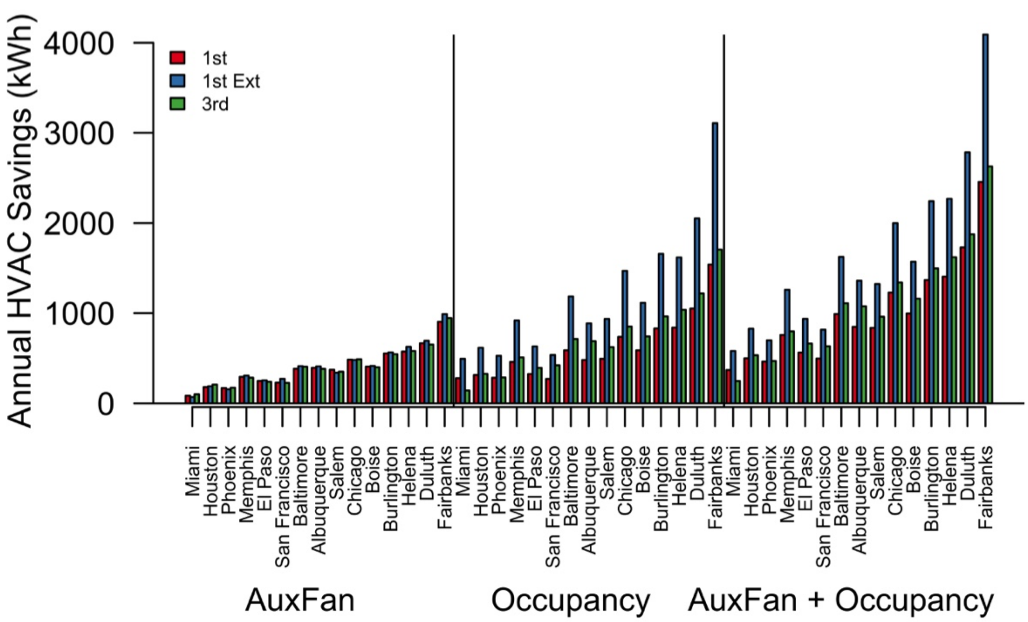

Figure 30 Half AEQ, NULL control baseline. Annual HVAC energy savings for each climate zone and fan control type, by occupancy schedule.

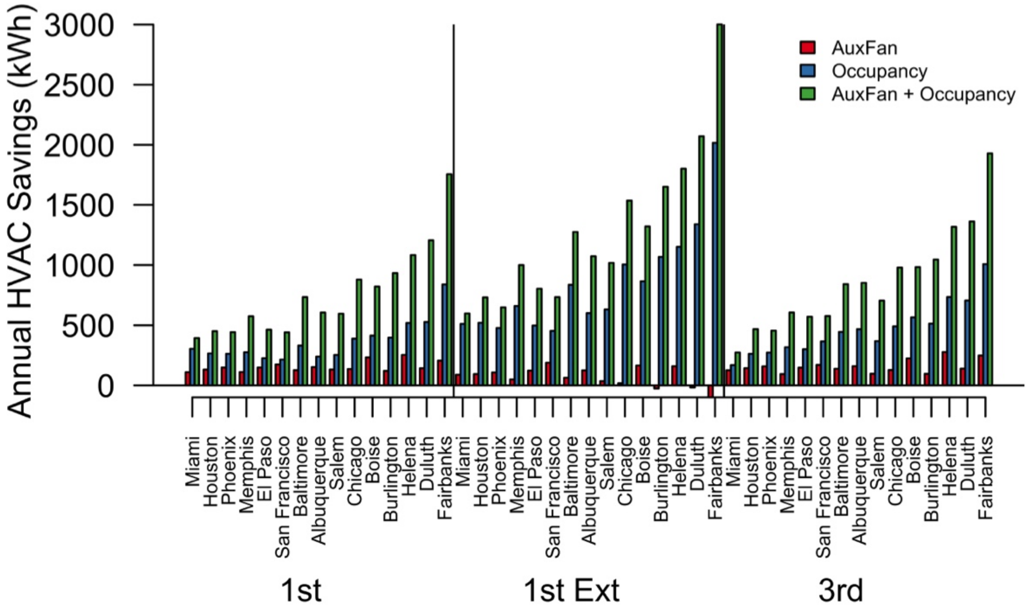

Figure 31 Half AEQ, continuous fan baseline. Annual HVAC energy savings for each climate zone and occupancy schedule, by fan control type.

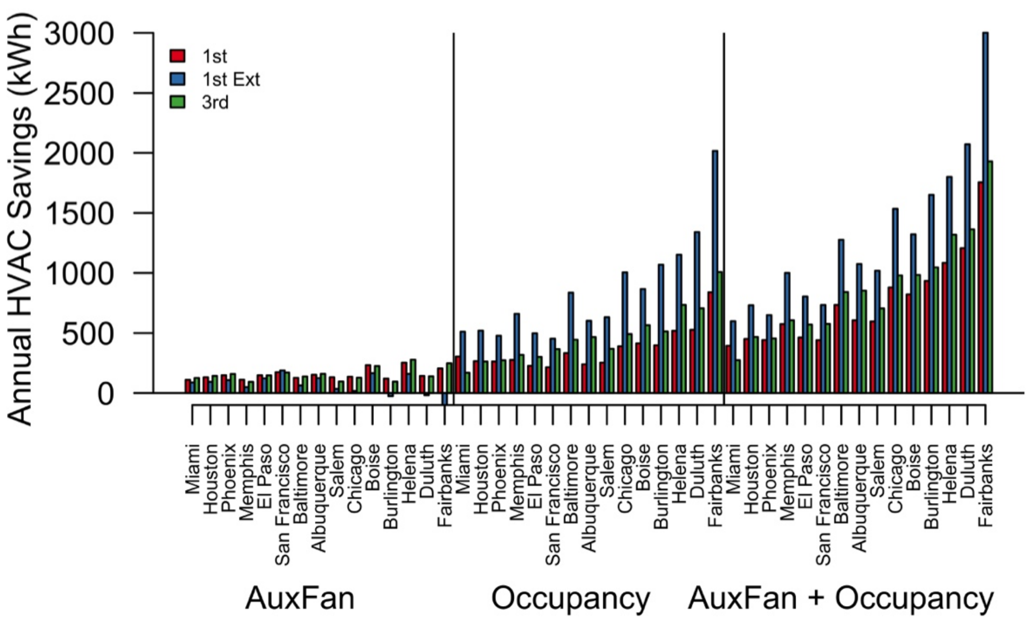

Figure 32 Half AEQ, continuous fan baseline. Annual HVAC energy savings for each climate zone and fan control type, by occupancy schedule.

4.4 Energy End-Uses

We assessed the energy end-use savings (kWh/year) for the exhaust fan cases with the NULL control for the baseline. End-uses savings estimates are not provided for the continuous fan baseline and balanced fan cases. End-use savings estimates are pictured for Auxiliary fan SVC in Figure 33, Occupancy SVC in Figure 34 (Full AEQ) and Figure 27 (Half AEQ), and Auxiliary Fan + Occupancy SVC in Figure 36 (Full

AEQ) and Figure 37 (Half AEQ). End-uses include disaggregated heating (Furnace), cooling (A/C), ventilation fan (Vent Fan) and central forced air blower (AHU) energy uses. Overall, energy savings were dominated by heating energy, which for a given control and occupancy pattern scaled linearly with climate severity. Many climate zones experienced marginal increased cooling energy consumption. For the Occupancy SVC, cooling savings were also modest in some warmer locations. The hottest climate (Miami) was the only location to be cooling energy dominated, with nearly no heating savings.

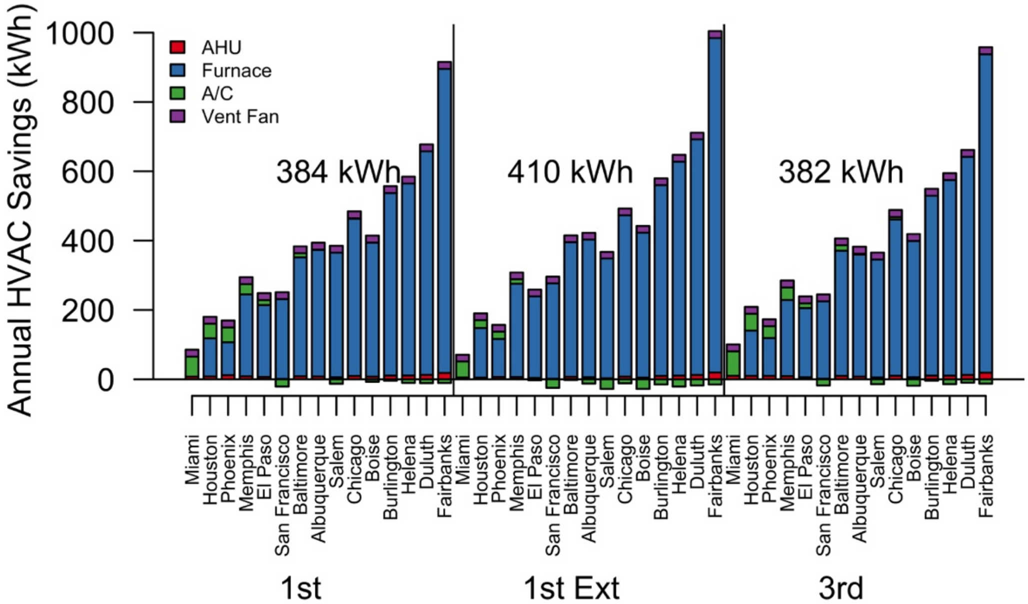

Figure 33 End-use HVAC energy savings for the Auxiliary Fan SVC. Median savings across climate zones for each occupancy schedule.

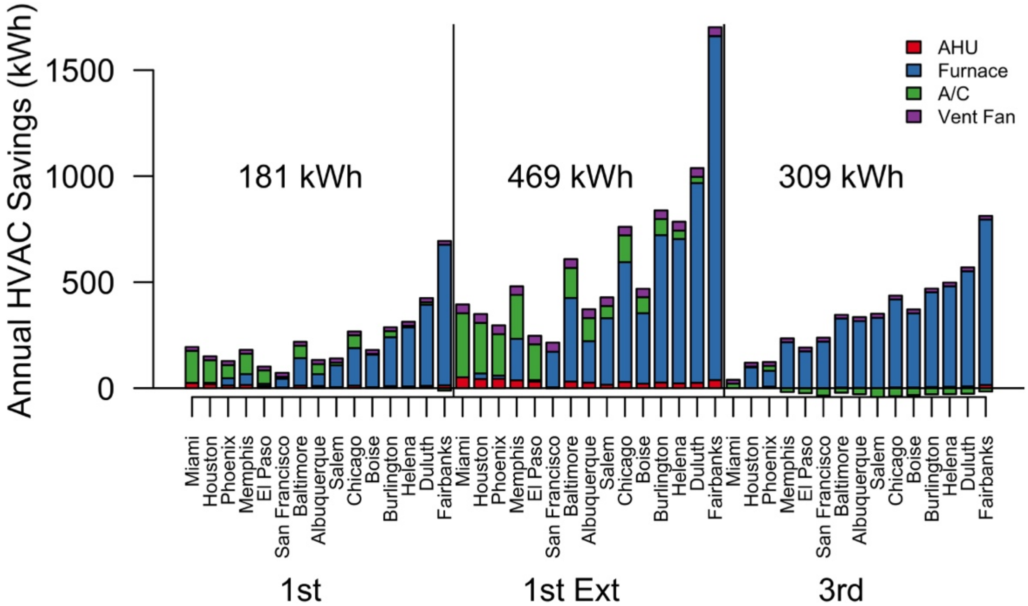

Figure 34 End-use HVAC energy savings for the Occupancy SVC. Median savings across climate zones for each occupancy schedule.

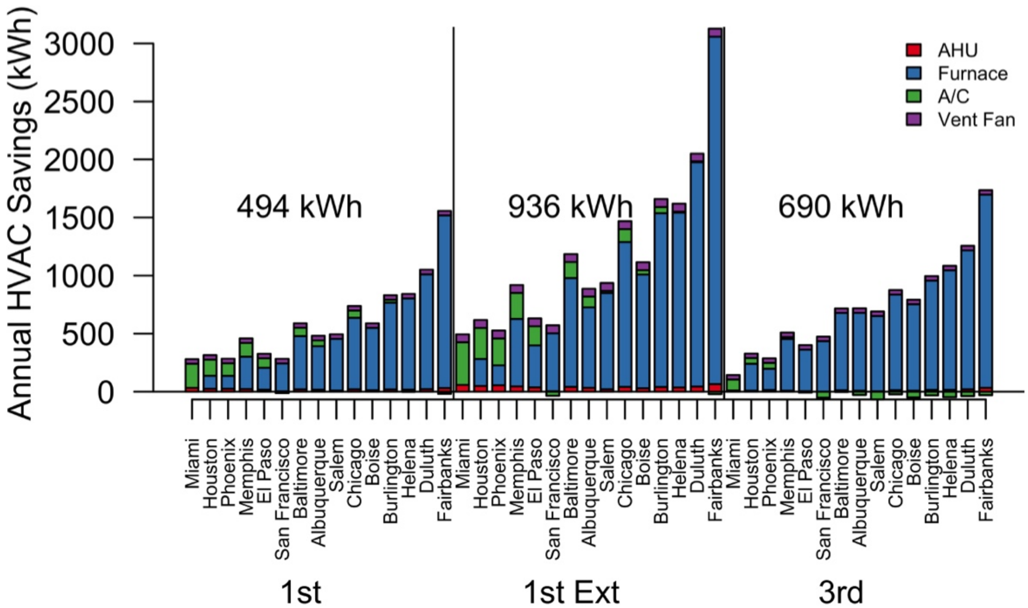

Figure 35 Half AEQ end-use HVAC energy savings for the Occupancy SVC. Median savings across climate zones for each occupancy schedule.

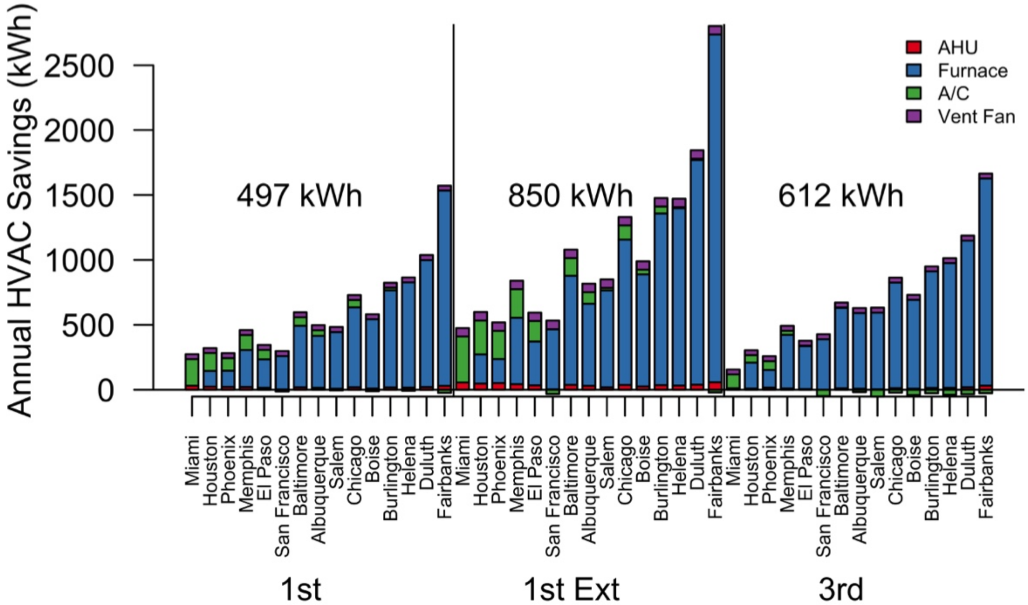

Figure 36 End-use HVAC energy savings for the Auxiliary Fan + Occupancy SVC. Median savings across climate zones for each occupancy schedule.

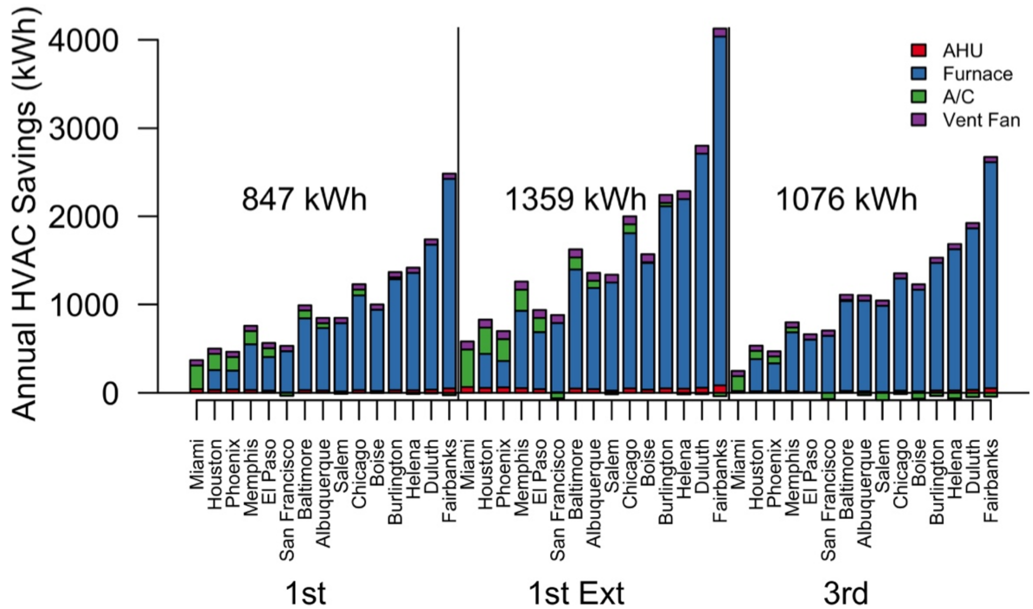

Figure 37 Half AEQ end-use HVAC energy savings for the Auxiliary Fan + Occupancy SVC. Median savings across climate zones for each occupancy schedule.

4.5 Balanced Fans

The results for balanced fans are easier to interpret because we do not have to consider the superposition effects associated with unbalanced fans. All Balanced fan control cases are simply compared with a continuous balanced fan, the NULL control is ignored. The Balanced Fans results are tabulated for each case in Appendix Table 18 (annual performance, energy, AER, relative dose and exposure) and Appendix Table 21 (annual savings kWh/yr).

The median annual average air exchange rate, relative exposure and dose were presented for each control type in Table 6. The continuous fan cases achieved the expected annual relative exposure almost exactly equal to one. The Aux Fan and Aux Fan + Occupancy controllers performed similarly, but the Occupancy controller had a slightly higher median relative exposure of 1.007. This was due to a slightly under-sized fan in these cases. Section 4.5.1 gives results for larger occupancy-controlled balanced fans showing that the larger fans effectively reduced relative exposure below one, with nearly no energy impact whatsoever, unlike the unbalanced fans discussed previously.

Occupancy Pattern	*Annual Reduction in Ventilation Energy (%)*		
	Aux Fan	*Occupancy*	*Aux Fan + Occupancy*
1st	12.0	7.0	18.8
1stExt	11.0	15.5	31.0
3rd	11.7	10.2	20.8
	Annual HVAC Energy Savings (kWh)		
1st	408	191	593
1stExt	414	476	969
3rd	391	368	732

Table 14 Balanced ventilation systems, continuous fan baseline. Annual reduction in the ventilation energy.

The median energy and percentage savings are summarized for each control and occupancy pattern in Table 14. The estimated percentage of ventilation-related energy use saved by the control strategies is pictured in Figure 38, and the absolute savings are shown for each location, occupancy pattern and control type in Figure 39 and Figure 40. Overall, the percent ventilation energy savings were very similar to those for the Full AEQ NULL control baseline, both of which were substantially higher than the savings calculated using the continuous fan baseline. The median savings across these categories are pictured for each control in Figure 41.

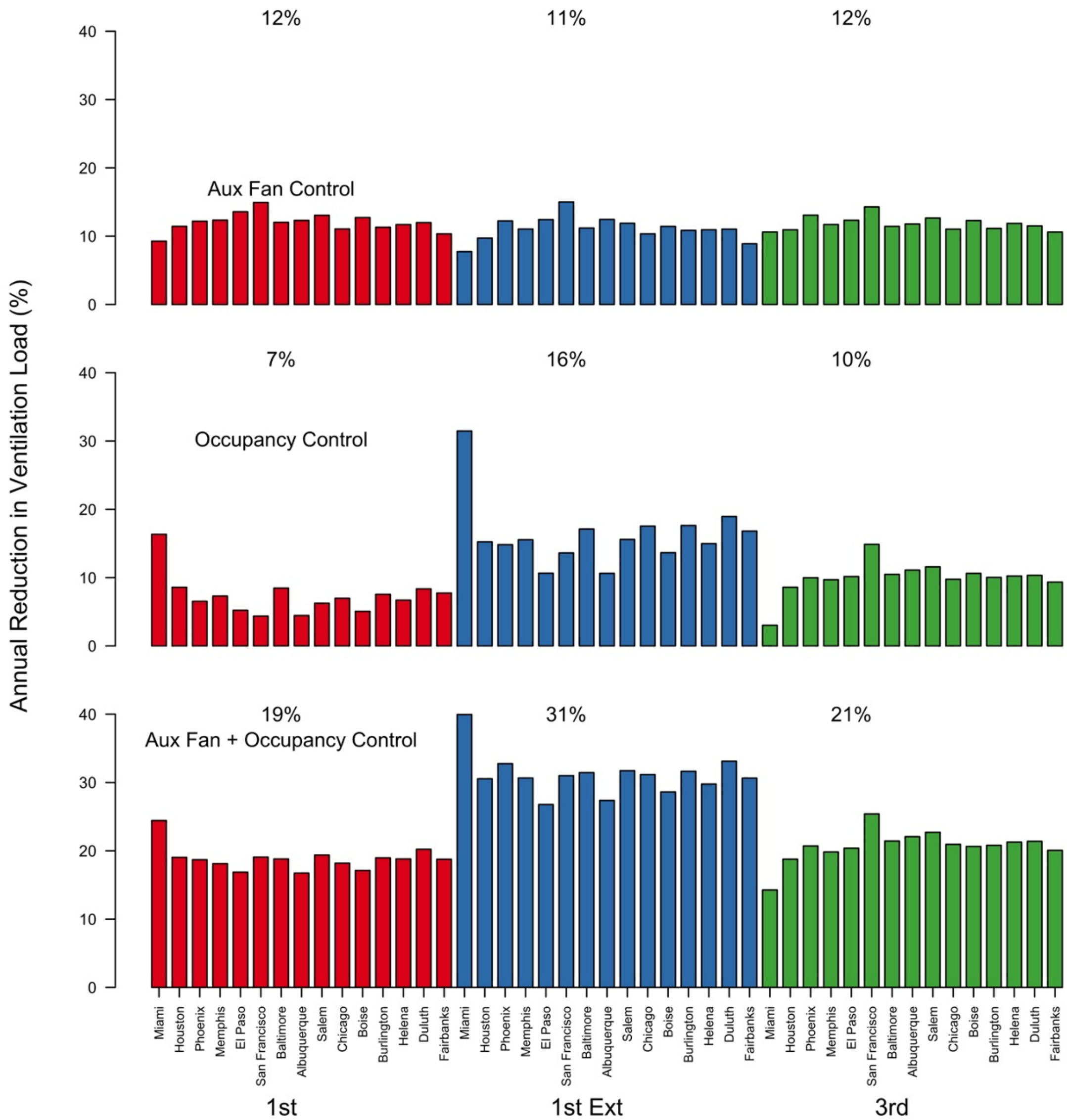

Figure 38 Balanced ventilation systems, continuous fan baseline. Annual percentage reduction in ventilation-related energy use, by control type and occupancy pattern.

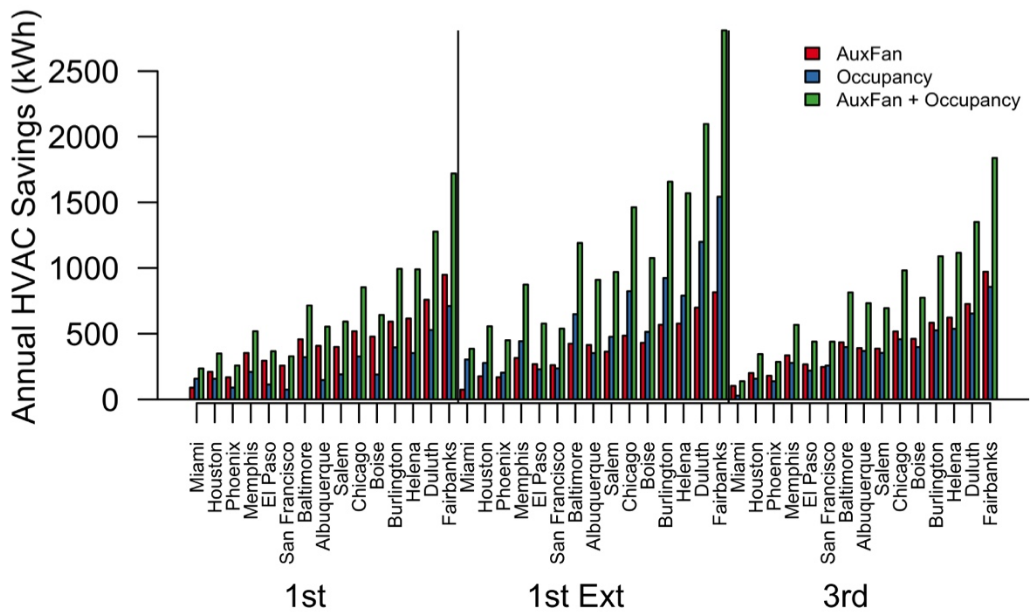

Figure 39 Balanced ventilation systems, continuous fan baseline. Annual HVAC energy savings, by control type.

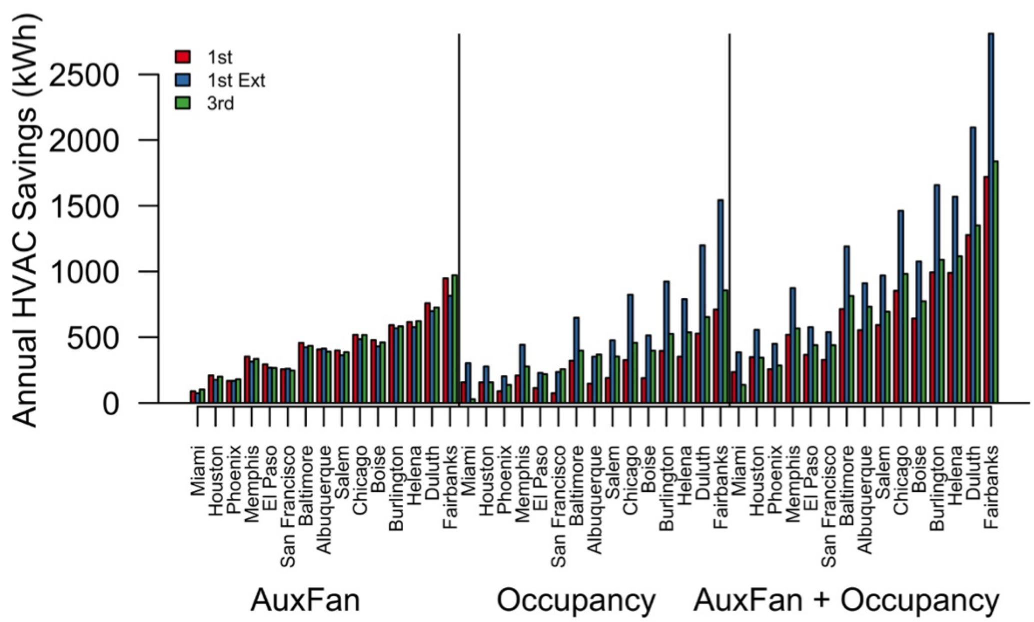

Figure 40 Balanced ventilation systems, continuous fan baseline. Annual HVAC energy savings, by occupancy pattern.

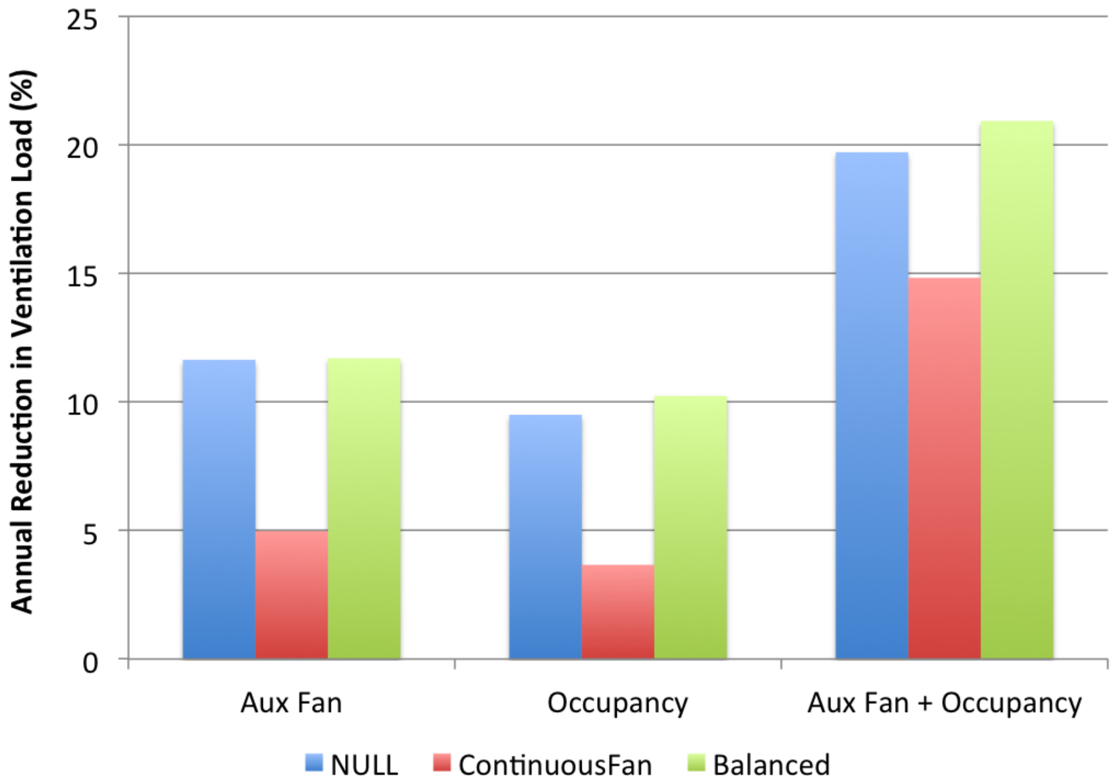

Figure 41 Median ventilation energy savings for each control type, comparing balanced fans and exhaust fans with NULL control and continuous fan baselines.

4.5.1 Fan Sizing Impacts

As noted above, the Occupancy controller achieved a median annual average relative dose of 1.007 in the balanced fan simulations (see Table 6). We hypothesized that this was the result of the fan size being too small, leading to a marginal increase in annual relative exposure, due to the length of the occupancy absence period and the recovery period. We assessed the impacts of using proportionally larger IAQ controlled fans in the Chicago test case, while fixing all other inputs. For all cases in the prior section, the balanced Occupancy control fan was sized at double the 62.2 requirement—71 l/s (100% oversizing). We then also tested fans oversized by 125, 150, 175 and 200% (89, 107, 124 and 142 l/s, respectively).

These fan size changes had very little effect on annual HVAC energy consumption, with a maximum difference between any fan sizes of 25 kWh (for the largest fan). This is because balanced fans were used in these cases, where cycling on and off larger fans has very marginal effect on the average air exchange rate. As discussed in Section 1.1.2, use of unbalanced exhaust fans would result in energy use changes, because of the superposition of unbalanced fans with natural infiltration.

As the over-sizing increased, the annual average relative exposure decreased, with all fans at 125-200% over-sizing achieving averages less than 1 (from 0.995 to. 0.977). So, modest increases in the fan over-sizing (e.g., from 100% to 125% over-sized) ensured that the control cases were equivalent, and they had almost no impact on energy use, while decreasing the annual relative exposure. Based on this finding using balanced ventilation fans, we argue that the effect of the NULL control for unbalanced fans is primarily to cancel out the super-position penalty of cycling on-and-off a larger fan, whereas shifting baseline relative exposure from slightly above to slightly below one has very little energy impact.

Increased fan size did reduce the recovery time period following the block of unoccupied hours. We have plotted an example day of relative exposure values across the five fan sizes tested in Figure 42 below. The unoccupied period is highlighted in light grey, and in all cases, the fans are turned off and the relative exposure increases. There are slight variations in their peak exposure due to the exact values at the start of the unoccupied period. Once occupants return home, the recovery periods begin, and here we see the clear ability of the larger fans to pull down relative exposure more quickly. The recovery periods end when the relative exposure reaches a minimum and begins to increase and then rapidly cycle up and down. From the largest to the smallest fan, this recovery period lasts 120 minutes, 151, 220, 300 and 450 minutes.

The relative dose values (time-integrated relative exposure) are shown in Figure 43 for these same cases and time periods. The reason the smaller fan has to operate for so long is because it is trying to control both exposure and dose to below 1. The small fan starts with the highest relative dose, which means it takes the longest to bring back below 1. The relative exposure also stays higher, longer with the small fan, so the growth in relative dose is greatest with the smaller fan. All of this leads to much longer recovery periods, and in the case of the original IAQ fan sized to double 62.2 requirements, the Occupancy control is not equivalent (annual relative exposure = 1.006). We still use the energy results from the balanced fan Occupancy cases, because as mentioned above, increasing fan size had essentially no impact on energy use, but did reduce relative exposure to the point of equivalence.

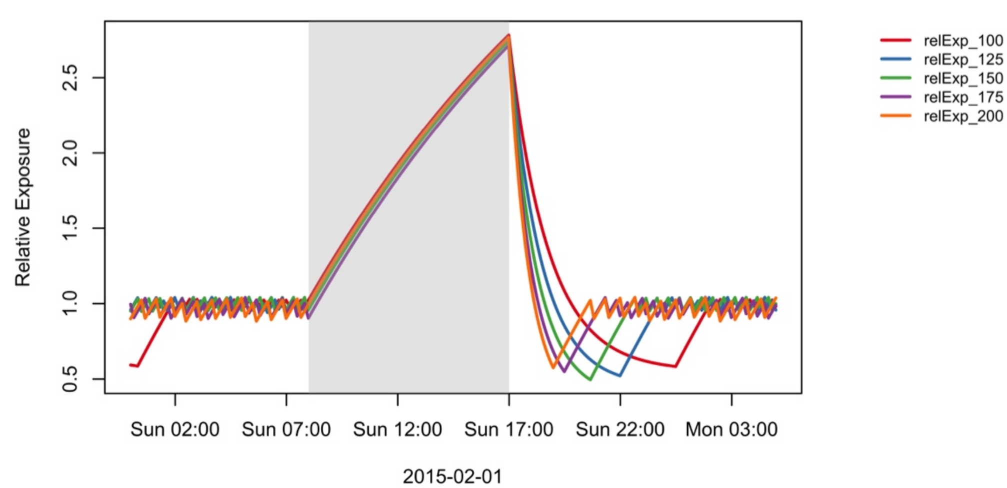

Figure 42 Comparison of recovery period duration for a variety of balanced IAQ fan sizes using the Occupancy control, Chicago test home example.

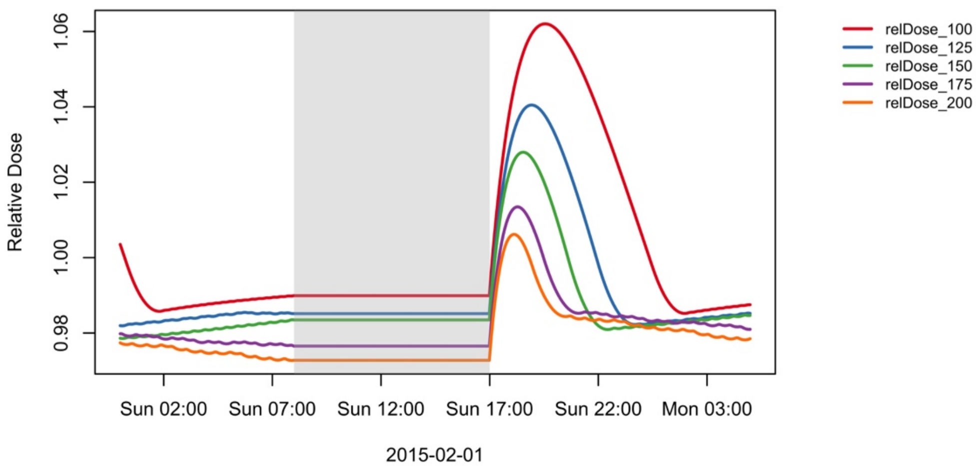

Figure 43 Comparison of relative dose time series values for a variety of balanced IAQ fan sizes using the Occupancy control, Chicago test home.

4.5.2 Recovery Period Parametric Analysis

We undertook a parametric evaluation of recovery time and fan sizing in order to separate recovery time from the different initial dose and exposure values arising in the annual simulations. Using an implementation of relative exposure and relative dose calculations (Equations 4 - 7) in the mathematical programming language R, we can estimate the required recovery period for different unoccupied durations, IAQ fan airflows, AEQ targets and infiltration rates. An example table is provided below, for a 200 m^2 home with a volume of 500 m^3. The 62.2-2016 Q_{tot} target is 44 l/s, and the estimated annual infiltration rate is 8.5 l/s. Table 15 shows the estimated recovery period in minutes for a matrix of unoccupied periods in hours (from 1 to 14 hours) and IAQ fan airflows varying from 10 to 100 l/s. For comparison to the REGCAP results detailed above—450-minute recovery period for the 71 l/s fan—Table 15 estimates that the 9-hour unoccupied period with a 70 l/s fan requires 476 minutes (green shading). The 89 l/s IAQ fan required 300 minutes to recover, and Table 15 estimates 325 minutes (purple shading). These values do not match exactly, because of slight differences in fan airflow and more importantly, the simplified calculations assume the dose and exposure start at exactly 1 at the beginning of the unoccupied period. We can see in Figure 43 the dose values begin between roughly in the range of 0.97 and 0.99, which accounts for the slightly shorter recovery periods. Designers could use a table like this to select an appropriate smart control fan size, based on the anticipated unoccupied period and infiltration rate.

IAQ Fan Airflow (m^3/s)	*Unoccupied Period (hrs.)*													
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***
0.01	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.015	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.02	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.025	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.03	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.035	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.04	546	863	1100	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
0.045	307	507	661	788	897	991	NA	NA	NA	NA	NA	NA	NA	NA
0.05	216	365	482	580	664	737	803	861	NA	NA	NA	NA	NA	NA
0.055	167	287	382	462	531	592	646	695	739	780	NA	NA	NA	NA
0.06	136	237	317	385	444	496	543	585	623	658	690	719	NA	NA
0.065	115	202	272	331	382	428	469	506	539	570	598	624	648	NA
0.07	100	176	238	290	336	376	413	446	**476**	504	529	552	573	593
0.075	88	156	211	258	300	336	369	399	426	451	474	495	515	533
0.08	79	140	190	233	271	304	334	361	386	409	430	449	467	484
0.085	71	127	173	212	247	278	305	330	353	374	394	411	428	443
0.09	65	116	159	195	227	255	281	304	**325**	345	363	379	395	409
0.095	60	107	147	180	210	236	260	282	302	320	337	352	366	380
0.1	55	99	136	168	195	220	242	263	281	298	314	328	342	354

Table 15 Estimated duration of the recovery time after absence periods of varying lengths, with varying IAQ fan sizes. Assumes an AEQ airflow of 44 l/s, natural infiltration of 8.5 l/s, and a house volume of 500 m^3.

5 Summary & Conclusions

Smart ventilation controls based on occupancy have been demonstrated alongside and in combination with controls sensing auxiliary fan operation in homes (e.g., vented clothes dryer, kitchen and bathroom fans). The controllers are based on the IAQ approach of using relative exposure and relative dose to control ventilation rates in real-time, with the goal of maintaining annual relative exposure below one (i.e., equivalent with a continuous fan sized to ASHRAE 62.2-2016). Example high performance homes complying with the DOE Zero Energy Ready program requirements were simulated using the REGCAP program across DOE climate zones with a variety of idealized occupancy patterns: 1st shift, an extended 1st shift and 3rd shift patterns. Occupancy controls turned the whole house IAQ fan off during unoccupied periods, leaving only natural infiltration to contribute to air exchange.

Smart controls were demonstrated that saved HVAC energy (i.e., combined heating/cooling load, AHU and IAQ fan energy) while maintaining annual equivalence with ASHRAE 62.2-2016. On average, between 6 and 46% of ventilation-related energy use was saved by the various smart controls, depending on the control strategy and occupancy pattern assumptions.

Overall, the energy savings from the Occupancy-based smart ventilation controls were low, averaging only 181 kWh/year for the 1st shift pattern (6% of ventilation energy), across U.S. DOE climate zones. Savings were greater in the 3rd shift pattern (309 kWh/year, 9%), as well as in the extended 1st shift pattern with greater unoccupied time periods (469 kWh/year, 17.4%). Energy savings increased with climate heating demand and longer unoccupied time periods. The 3rd shift occupancy pattern had better performance, due to the thermal benefit of reducing the ventilation rate during the cold nighttime hours (this same effect provided a cooling energy benefit in hotter locations for the 1st shift). Percentage savings was fairly consistent across climate zones.

Savings were low, because much of the benefit of turning off the ventilation system during unoccupied time periods is eliminated, as the smart controller must over-ventilate to maintain equivalence with ASHRAE 62.2 during the recovery period immediately after occupants return home. The common pattern was for the ventilation to be off for 9-hours, and then the airflow was doubled for roughly 6-hours in order to recover and maintain equivalence, resulting in only a net-reduction in daily airflow of roughly 12% (3/24). This is sharply distinguished from past demand controlled ventilation systems, where fans were simply turned off during unoccupied periods, resulting in daily airflow reductions of nearly 40% (9/24). These DCV controls did not account for unoccupied emissions, and would not comply with the ASHRAE ventilation standard.

We demonstrated a number of ways to increase these energy savings for smart ventilation controls based on occupancy that maintain equivalence. First, combining occupancy controls with auxiliary fan sensing substantially improved energy performance (ventilation energy savings increased from 6 to 17% for 1st shift Full AEQ). Second, we demonstrated that if the ASHRAE standard assumed lower pollutant emissions during unoccupied periods, and allowed a lower target ventilation rate during these times, then the energy performance for occupancy controls would improve similarly (from 6 to 17% of ventilation energy saved, see Full vs. Half AEQ sections). Finally, we showed that use of a pre-occupancy flush-out would reduce the recovery period, allowing for greater reductions in daily airflow. This increased energy performance similar to the Half AEQ approach. The pre-occupancy flush out would also reduce the peak relative exposure experienced by the occupants.

When using the assumptions of the current ASHRAE 62.2 (Full AEQ, constant emissions), the maximum average reduction in ventilation energy use due to occupancy-based controls was 30%. This was for the extended 1st shift pattern, with combined occupancy- and auxiliary fan smart controls. Results in this case were similar for unbalanced and balanced ventilation fans.

6 References

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2015). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environmental Health Perspectives*. https://doi.org/10.1289/ehp.1510037

ANSES. (2013). *Concentrations de CO2 dans l'air intérieur et effets sur la santé - Edition scientifique* (No. 2012-NaN-93). ANSES. Retrieved from https://www.anses.fr/en/system/files/AIR2012sa0093Ra.pdf

ANSI/ASHRAE. (2016). *Standard 62.2-2016 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta, GA: ASHRAE.

ASHRAE. (2013). *2013 ASHRAE Handbook - Fundamentals* (SI). Atlanta, GA: ASHRAE.

Chenari, B., Dias Carrilho, J., & Gameiro da Silva, M. (2016). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renewable and Sustainable Energy Reviews*, *59*, 1426–1447. https://doi.org/10.1016/j.rser.2016.01.074

Danish Enterprise and Construction Authority. (2010). *Danish Building Regulations 2010, BR10*. Copenhagen, Denmark: The Danish Ministry of Economic and Business Affairs. Retrieved from http://www.buildup.eu/sites/default/files/content/BR10_ENGLISH.pdf

Emmerich, S. J., & Persily, A. K. (2001). *State-of-the-Art Review of CO2 Demand Controlled Ventilation Technology and Application* (No. NISTIR 6729). Washington, D.C.: National Institute of Standards and Technology. Retrieved from http://fire.nist.gov/bfrlpubs/build01/PDF/b01117.pdf

Fisk, W. J., & De Almeida, A. T. (1998). Sensor-based demand-controlled ventilation: a review. *Energy and Buildings*, *29*(1), 35–45. https://doi.org/10.1016/S0378-7788(98)00029-2

Her Majesty's Government. (2010). *The Building Regulations 2010, Approved Document F, Ventilation* (2010 Edition Incorporating 2010 and 2013 admendments). United Kingdom: Her Majesty's Government. Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/468871/ADF_LOCKED.pdf

Hesaraki, A., & Holmberg, S. (2015). Demand-controlled ventilation in new residential buildings: Consequences on indoor air quality and energy savings. *Indoor and Built Environment*, *24*(2), 162–173. https://doi.org/10.1177/1420326X13508565

Hurel, N., Sherman, M. H., & Walker, I. S. (2016). Sub-additivity in combining infiltration with mechanical ventilation for single zone buildings. *Building and Environment*, *98*, 89–97. https://doi.org/10.1016/j.buildenv.2015.12.020

Laverge, J., Bossche, N. V. D., Heijmans, N., & Janssens, A. (2011). Energy saving potential and repercussions on indoor air quality of demand controlled residential ventilation strategies. *Building and Environment*, *46*(7), 1497–1503.

Max von Pettenkofer. (1858). *Über den Luftwechsel in Wohngebäuden*. Cotta.

Mortensen, D. K., Walker, I. S., & Sherman, M. H. (2011a). Optimization of occupancy based demand controlled ventilation in residences. *International Journal of Ventilation*, *10*(1), 49–60.

Mortensen, D. K., Walker, I. S., & Sherman, M. H. (2011b). Optimization of Occupancy Based Demand Controlled Ventilation in Residences. *International Journal of Ventilation*, *10*(1), 49–60. https://doi.org/10.1080/14733315.2011.11683934

Nazaroff, W. W. (2009). What does "average" mean for time-varying air-exchange rates? *9th International Conference and Exhibition - Healthy Buildings 2009, HB 2009*.

Raatschen, W. (1990a). *IEA Annex 18. Demand controlled ventilating system: state of the art review*. (IEA Energy Conservation in Buildings & Community Systems Program, Ed.). Stockholm, Sweden: Swedish Council for Building Research.

Raatschen, W. (1990b). IEA Annex 18. Demand Controlled Ventilating Systems: State of the Art Review. Swedish Council for Building Research.

Ramalho, O., Wyart, G., Mandin, C., Blondeau, P., Cabanes, P.-A., Leclerc, N., … Redaelli, M. (2015). Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values. *Building and Environment*, *93*, 115–124. https://doi.org/10.1016/j.buildenv.2015.03.018

Romer, J. C., & Van Ginkel, J. T. (2003). Demand controlled ventilation in a low-energy house: Preliminary results on energy conservation and health effects. Presented at the The 4th International Conference on Cold Climate - Heating, Ventilating and Air-conditioning, HVAC CC. Retrieved from http://resolver.tudelft.nl/uuid:58163d1b-c276-4898-9e7a-5535d7d329ca

Sherman, M. H. (2004). *Efficacy of intermittent ventilation for providing acceptable indoor air quality* (No. LBNL--56292, 834643). Retrieved from http://www.osti.gov/servlets/purl/834643-ervtNw/native/

Sherman, M. H., Logue, J. M., & Singer, B. C. (2011). Infiltration effects on residential pollutant concentrations for continuous and intermittent mechanical ventilation approaches. *HVAC&R Research*, *17*(2), 159–173. https://doi.org/10.1080/10789669.2011.543258

Sherman, M. H., Mortensen, D. K., & Walker, I. S. (2011a). Derivation of equivalent continuous dilution for cyclic, unsteady driving forces. *International Journal of Heat and Mass Transfer*, *54*(11–12), 2696–2702. https://doi.org/10.1016/j.ijheatmasstransfer.2010.12.018

Sherman, M. H., Mortensen, D. K., & Walker, I. S. (2011b). Derivation of equivalent continuous dilution for cyclic, unsteady driving forces. *International Journal of Heat and Mass Transfer*, *54*(11–12), 2696–2702. https://doi.org/10.1016/j.ijheatmasstransfer.2010.12.018

Sherman, M. H., & Walker, I. S. (2011). Meeting Residential Ventilation Standards through Dynamic Control of Ventilation Systems. *Energy and Buildings*, *43*(8), 1904–1912. https://doi.org/10.1016/j.enbuild.2011.03.037

Sherman, M. H., Walker, I. S., & Logue, J. M. (2012). Equivalence in ventilation and indoor air quality. *HVAC&R Research*, *18*(4), 760–773. https://doi.org/10.1080/10789669.2012.667038

Turner, W. J. N., & Sherman, M. H. (2012). Infiltration as ventilation: Weather-induced dilution. *HVAC&R Research*, *18*(6), 1122–1135. https://doi.org/10.1080/10789669.2012.704836

Turner, W. J. N., Walker, I. S., & Sherman, M. (2014). *Advanced Controls for Residential Whole-House Ventilation Systems* (No. LBNL-6882E). Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from https://buildings.lbl.gov/publications/advanced-controls-residential-whole

U.S. Department of Energy. (2013, April 17). DOE Challenge Home National Program Requirements (Rev. 03). U.S. Department of Energy. Retrieved from http://www1.eere.energy.gov/buildings/residential/pdfs/doe_challenge_home_requirementsv3.pdf

Walker, I. S. (1993, Spring). *Attic Ventilation, Heat and Moisture Transfer*. University of Alberta, Edmonton, Alberta.

Walker, I. S., Forest, T. W., & Wilson, D. J. (2005). An attic-interior infiltration and interzone transport model of a house. *Building and Environment*, *40*(5), 701–718. https://doi.org/10.1016/j.buildenv.2004.08.002

Walker, I. S., & Sherman, M. H. (2006). *Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements* (No. LBNL-59998). Berkeley, CA: Lawrence Berkeley National Lab. Retrieved from https://buildings.lbl.gov/sites/all/files/lbnl-59998.pdf

Wilson, D. J., & Walker, I. S. (1990). Combining Air Infiltration and Exhaust Ventilation. In *Indoor Air 90'* (pp. 467–472). Toronto, Canada.

Zhang, X., Wargocki, P., & Lian, Z. (2017). Physiological responses during exposure to carbon dioxide and bioeffluents at levels typically occurring indoors. *Indoor Air*, *27*(1), 65–77. https://doi.org/10.1111/ina.12286

7 Appendix

Occupancy	CZ	Control	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mechanical Ventilation (kWh/yr)	Total (kWh/yr)	Air Exchange Rate (hr^{-1})	Avg Relative Exposure	Avg Relative Dose
1st	Miami	No IAQ fan	1135	21	5049	14	6219	0.089	5.050	5.039
1st	Miami	Continuous IAQ fan	1245	21	5865	224	7355	0.340	1.005	1.005
1st	Miami	Aux Fan	1236	21	5800	188	7245	0.317	0.989	0.989
1st	Miami	Occupancy	1219	21	5706	190	7136	0.324	1.001	1.001
1st	Miami	Aux Fan + Occupancy	1212	21	5653	170	7056	0.297	0.993	0.993
1st	Miami	NULL Control	1243	21	5858	208	7330	0.345	0.996	0.996
1st	Houston	No IAQ fan	874	3910	3510	14	8309	0.099	4.930	4.919
1st	Houston	Continuous IAQ fan	966	4806	4052	223	10048	0.340	1.005	1.005
1st	Houston	Aux Fan	958	4773	3999	187	9917	0.322	0.989	0.989
1st	Houston	Occupancy	948	4876	3935	188	9947	0.327	1.001	1.001
1st	Houston	Aux Fan + Occupancy	941	4762	3903	169	9776	0.301	0.993	0.993
1st	Houston	NULL Control	966	4883	4042	207	10097	0.349	0.997	0.997
1st	Phoenix	No IAQ fan	1268	2203	5280	14	8765	0.083	4.816	4.805
1st	Phoenix	Continuous IAQ fan	1356	2993	5626	223	10197	0.337	1.006	1.006
1st	Phoenix	Aux Fan	1346	2928	5588	187	10049	0.312	0.988	0.988
1st	Phoenix	Occupancy	1345	2989	5569	188	10091	0.316	1.000	1.000
1st	Phoenix	Aux Fan + Occupancy	1335	2898	5534	169	9937	0.289	0.993	0.993
1st	Phoenix	NULL Control	1358	3023	5631	207	10219	0.339	0.996	0.996
1st	Memphis	No IAQ fan	781	5954	3334	14	10083	0.102	5.401	5.389
1st	Memphis	Continuous IAQ fan	868	7722	3756	225	12570	0.343	1.004	1.004
1st	Memphis	Aux Fan	863	7688	3719	190	12459	0.327	0.988	0.988
1st	Memphis	Occupancy	856	7873	3653	192	12573	0.334	1.000	1.000
1st	Memphis	Aux Fan + Occupancy	849	7639	3633	172	12294	0.308	0.993	0.993
1st	Memphis	NULL Control	871	7924	3749	210	12754	0.355	0.995	0.995
1st	El Paso	No IAQ fan	782	3223	3578	14	7597	0.093	5.176	5.165
1st	El Paso	Continuous IAQ fan	842	4765	3768	224	9599	0.340	1.005	1.005
1st	El Paso	Aux Fan	837	4679	3746	189	9451	0.320	0.988	0.988

1st	El Paso	Occupancy	833	4876	3697	191	9597	0.326	1.000	1.000
1st	El Paso	Aux Fan + Occupancy	827	4667	3688	171	9354	0.299	0.993	0.993
1st	El Paso	NULL Control	843	4886	3761	209	9699	0.348	0.995	0.995
1st	San Francisco	No IAQ fan	256	2588	1011	14	3869	0.106	4.142	4.134
1st	San Francisco	Continuous IAQ fan	257	4167	836	220	5479	0.334	1.009	1.009
1st	San Francisco	Aux Fan	257	4013	853	182	5306	0.318	0.988	0.988
1st	San Francisco	Occupancy	256	4201	824	183	5463	0.323	0.999	0.999
1st	San Francisco	Aux Fan + Occupancy	255	3987	845	163	5250	0.297	0.992	0.992
1st	San Francisco	NULL Control	259	4243	832	202	5536	0.345	0.995	0.996
1st	Baltimore	No IAQ fan	652	9723	2215	14	12605	0.104	4.969	4.959
1st	Baltimore	Continuous IAQ fan	732	12463	2407	223	15825	0.340	1.005	1.005
1st	Baltimore	Aux Fan	728	12393	2389	188	15698	0.325	0.989	0.989
1st	Baltimore	Occupancy	725	12606	2343	189	15863	0.331	1.001	1.002
1st	Baltimore	Aux Fan + Occupancy	718	12263	2335	170	15486	0.305	0.993	0.993
1st	Baltimore	NULL Control	737	12736	2401	207	16082	0.352	0.997	0.997
1st	Albuquerque	No IAQ fan	648	7202	2435	14	10299	0.106	4.602	4.592
1st	Albuquerque	Continuous IAQ fan	709	9725	2481	222	13137	0.338	1.007	1.007
1st	Albuquerque	Aux Fan	706	9616	2477	186	12985	0.324	0.987	0.987
1st	Albuquerque	Occupancy	705	9925	2431	187	13246	0.328	0.999	0.999
1st	Albuquerque	Aux Fan + Occupancy	698	9581	2435	167	12882	0.302	0.992	0.992
1st	Albuquerque	NULL Control	714	9981	2478	206	13379	0.351	0.993	0.993
1st	Salem	No IAQ fan	458	6518	1842	14	8832	0.116	4.518	4.509
1st	Salem	Continuous IAQ fan	489	8946	1713	222	11370	0.340	1.007	1.007
1st	Salem	Aux Fan	489	8844	1720	185	11238	0.329	0.987	0.987
1st	Salem	Occupancy	490	9100	1695	186	11471	0.334	0.999	0.999
1st	Salem	Aux Fan + Occupancy	486	8768	1712	166	11132	0.309	0.992	0.992
1st	Salem	NULL Control	494	9204	1707	205	11611	0.356	0.994	0.994
1st	Chicago	No IAQ fan	647	11195	2352	14	14208	0.105	5.176	5.165
1st	Chicago	Continuous IAQ fan	727	14741	2442	224	18135	0.341	1.005	1.005
1st	Chicago	Aux Fan	726	14645	2439	189	17999	0.327	0.988	0.988
1st	Chicago	Occupancy	724	14921	2380	191	18216	0.334	1.000	1.000
1st	Chicago	Aux Fan + Occupancy	715	14484	2384	171	17754	0.307	0.993	0.993
1st	Chicago	NULL Control	735	15099	2440	209	18484	0.355	0.995	0.995

1st	Boise	No IAQ fan	577	7816	2338	14	10746	0.091	5.545	5.533
1st	Boise	Continuous IAQ fan	631	11002	2212	225	14071	0.340	1.004	1.004
1st	Boise	Aux Fan	627	10805	2215	191	13839	0.322	0.988	0.988
1st	Boise	Occupancy	631	11038	2205	193	14066	0.327	1.001	1.001
1st	Boise	Aux Fan + Occupancy	625	10658	2219	173	13676	0.301	0.993	0.994
1st	Boise	NULL Control	635	11192	2208	211	14246	0.350	0.994	0.994
1st	Burlington	No IAQ fan	584	12556	1770	14	14924	0.112	5.091	5.080
1st	Burlington	Continuous IAQ fan	665	16520	1763	224	19173	0.341	1.005	1.005
1st	Burlington	Aux Fan	664	16435	1765	188	19053	0.330	0.988	0.988
1st	Burlington	Occupancy	666	16730	1733	190	19319	0.338	1.000	1.001
1st	Burlington	Aux Fan + Occupancy	656	16215	1741	171	18782	0.311	0.993	0.993
1st	Burlington	NULL Control	675	16962	1761	208	19606	0.358	0.995	0.995
1st	Helena	No IAQ fan	535	11987	1535	14	14071	0.097	4.930	4.919
1st	Helena	Continuous IAQ fan	613	16347	1405	223	18589	0.337	1.005	1.005
1st	Helena	Aux Fan	610	16125	1414	187	18336	0.320	0.989	0.989
1st	Helena	Occupancy	613	16400	1396	188	18597	0.325	1.001	1.001
1st	Helena	Aux Fan + Occupancy	604	15869	1411	169	18052	0.299	0.993	0.993
1st	Helena	NULL Control	621	16679	1404	207	18910	0.347	0.997	0.997
1st	Duluth	No IAQ fan	565	16256	1160	14	17995	0.112	4.438	4.428
1st	Duluth	Continuous IAQ fan	658	21190	1069	221	23139	0.337	1.007	1.007
1st	Duluth	Aux Fan	658	21073	1081	185	22997	0.325	0.988	0.988
1st	Duluth	Occupancy	661	21335	1059	185	23239	0.330	1.000	1.000
1st	Duluth	Aux Fan + Occupancy	649	20741	1071	166	22628	0.304	0.992	0.992
1st	Duluth	NULL Control	671	21718	1070	204	23664	0.352	0.995	0.995
1st	Fairbanks	No IAQ fan	746	25987	886	14	27632	0.094	5.914	5.900
1st	Fairbanks	Continuous IAQ fan	897	33416	772	226	35311	0.341	1.003	1.003
1st	Fairbanks	Aux Fan	894	33237	783	192	35106	0.325	0.989	0.989
1st	Fairbanks	Occupancy	899	33451	784	194	35328	0.331	1.002	1.003
1st	Fairbanks	Aux Fan + Occupancy	882	32610	796	175	34463	0.305	0.995	0.995
1st	Fairbanks	NULL Control	913	34114	772	212	36011	0.353	0.996	0.996
1stExt	Miami	No IAQ fan	1132	21	5038	14	6204	0.090	5.050	5.039
1stExt	Miami	Continuous IAQ fan	1241	21	5847	224	7333	0.341	1.005	1.005
1stExt	Miami	Aux Fan	1235	21	5801	188	7245	0.322	0.977	0.977
1stExt	Miami	Occupancy	1190	21	5545	166	6921	0.298	1.001	1.002

1stExt	Miami	Aux Fan + Occupancy	1184	21	5493	142	6841	0.265	0.992	0.993
1stExt	Miami	NULL Control	1241	21	5847	207	7316	0.350	0.985	0.985
1stExt	Houston	No IAQ fan	871	3936	3495	14	8315	0.100	4.930	4.919
1stExt	Houston	Continuous IAQ fan	962	4839	4028	223	10052	0.341	1.005	1.005
1stExt	Houston	Aux Fan	959	4811	4003	187	9959	0.328	0.977	0.977
1stExt	Houston	Occupancy	921	4927	3787	165	9800	0.302	1.001	1.002
1stExt	Houston	Aux Fan + Occupancy	916	4729	3765	141	9551	0.271	0.992	0.993
1stExt	Houston	NULL Control	964	4953	4026	207	10150	0.355	0.984	0.984
1stExt	Phoenix	No IAQ fan	1263	2236	5257	14	8769	0.084	4.816	4.805
1stExt	Phoenix	Continuous IAQ fan	1350	3008	5603	223	10184	0.337	1.006	1.006
1stExt	Phoenix	Aux Fan	1347	2952	5592	186	10077	0.315	0.978	0.978
1stExt	Phoenix	Occupancy	1310	3046	5417	164	9938	0.288	1.001	1.002
1stExt	Phoenix	Aux Fan + Occupancy	1302	2877	5396	140	9715	0.256	0.992	0.993
1stExt	Phoenix	NULL Control	1354	3061	5613	205	10234	0.343	0.986	0.986
1stExt	Memphis	No IAQ fan	779	5989	3318	14	10100	0.103	5.401	5.389
1stExt	Memphis	Continuous IAQ fan	865	7751	3736	225	12576	0.343	1.004	1.004
1stExt	Memphis	Aux Fan	864	7757	3717	190	12527	0.333	0.977	0.977
1stExt	Memphis	Occupancy	833	7830	3523	169	12355	0.310	1.003	1.003
1stExt	Memphis	Aux Fan + Occupancy	827	7515	3510	145	11996	0.278	0.993	0.994
1stExt	Memphis	NULL Control	870	8026	3730	209	12835	0.360	0.985	0.985
1stExt	El Paso	No IAQ fan	778	3275	3557	14	7624	0.093	5.176	5.165
1stExt	El Paso	Continuous IAQ fan	838	4814	3744	224	9621	0.340	1.005	1.005
1stExt	El Paso	Aux Fan	837	4731	3742	188	9498	0.325	0.978	0.978
1stExt	El Paso	Occupancy	810	4959	3570	167	9507	0.300	1.002	1.002
1stExt	El Paso	Aux Fan + Occupancy	806	4629	3582	143	9160	0.268	0.993	0.993
1stExt	El Paso	NULL Control	841	4966	3740	208	9754	0.352	0.987	0.987
1stExt	San Francisco	No IAQ fan	255	2612	1005	14	3887	0.107	4.142	4.134
1stExt	San Francisco	Continuous IAQ fan	258	4209	831	220	5518	0.334	1.009	1.009
1stExt	San Francisco	Aux Fan	257	4041	850	181	5330	0.324	0.976	0.976
1stExt	San Francisco	Occupancy	255	4148	826	158	5388	0.299	0.998	0.999
1stExt	San Francisco	Aux Fan + Occupancy	255	3854	856	134	5099	0.267	0.990	0.991
1stExt	San Francisco	NULL Control	259	4317	825	201	5601	0.351	0.983	0.983
1stExt	Baltimore	No IAQ fan	651	9775	2200	14	12639	0.105	4.969	4.959

1stExt	Baltimore	Continuous IAQ fan	730	12511	2391	223	15855	0.340	1.005	1.005
1stExt	Baltimore	Aux Fan	730	12488	2387	187	15792	0.331	0.977	0.977
1stExt	Baltimore	Occupancy	706	12482	2243	165	15596	0.306	1.001	1.002
1stExt	Baltimore	Aux Fan + Occupancy	699	12036	2249	142	15125	0.275	0.992	0.993
1stExt	Baltimore	NULL Control	737	12876	2385	207	16205	0.358	0.984	0.984
1stExt	Albuquerque	No IAQ fan	646	7256	2423	14	10338	0.107	4.602	4.592
1stExt	Albuquerque	Continuous IAQ fan	707	9805	2464	222	13197	0.338	1.007	1.007
1stExt	Albuquerque	Aux Fan	708	9706	2474	184	13072	0.329	0.978	0.979
1stExt	Albuquerque	Occupancy	688	9907	2353	162	13111	0.303	1.000	1.001
1stExt	Albuquerque	Aux Fan + Occupancy	683	9472	2373	139	12666	0.272	0.992	0.992
1stExt	Albuquerque	NULL Control	714	10103	2462	204	13483	0.355	0.986	0.986
1stExt	Salem	No IAQ fan	456	6564	1824	14	8858	0.117	4.518	4.509
1stExt	Salem	Continuous IAQ fan	487	8988	1692	222	11389	0.340	1.007	1.007
1stExt	Salem	Aux Fan	491	8964	1715	184	11354	0.334	0.979	0.979
1stExt	Salem	Occupancy	478	8996	1630	162	11265	0.310	1.000	1.000
1stExt	Salem	Aux Fan + Occupancy	474	8564	1668	138	10844	0.279	0.992	0.992
1stExt	Salem	NULL Control	494	9310	1688	203	11694	0.360	0.988	0.988
1stExt	Chicago	No IAQ fan	645	11243	2337	14	14240	0.106	5.176	5.165
1stExt	Chicago	Continuous IAQ fan	726	14776	2427	224	18152	0.341	1.005	1.005
1stExt	Chicago	Aux Fan	728	14782	2437	188	18135	0.333	0.978	0.978
1stExt	Chicago	Occupancy	707	14682	2299	167	17855	0.310	1.002	1.002
1stExt	Chicago	Aux Fan + Occupancy	699	14128	2315	143	17286	0.278	0.993	0.993
1stExt	Chicago	NULL Control	736	15247	2425	208	18616	0.360	0.987	0.987
1stExt	Boise	No IAQ fan	574	7866	2315	14	10769	0.091	5.545	5.533
1stExt	Boise	Continuous IAQ fan	628	11042	2188	225	14083	0.340	1.004	1.004
1stExt	Boise	Aux Fan	628	10888	2211	190	13918	0.327	0.977	0.977
1stExt	Boise	Occupancy	613	10973	2108	170	13864	0.302	1.003	1.004
1stExt	Boise	Aux Fan + Occupancy	607	10444	2147	146	13344	0.269	0.993	0.994
1stExt	Boise	NULL Control	633	11306	2184	210	14333	0.354	0.984	0.984
1stExt	Burlington	No IAQ fan	583	12603	1757	14	14957	0.112	5.091	5.080
1stExt	Burlington	Continuous IAQ fan	663	16559	1749	224	19195	0.341	1.005	1.005
1stExt	Burlington	Aux Fan	667	16604	1762	188	19221	0.337	0.978	0.978
1stExt	Burlington	Occupancy	650	16459	1671	167	18948	0.314	1.002	1.002
1stExt	Burlington	Aux Fan +	641	15833	1694	143	18309	0.282	0.992	0.993

		Occupancy								
1stExt	Burlington	NULL Control	677	17154	1747	207	19786	0.364	0.986	0.986
1stExt	Helena	No IAQ fan	534	12046	1521	14	14116	0.097	4.930	4.919
1stExt	Helena	Continuous IAQ fan	613	16418	1391	223	18645	0.338	1.005	1.005
1stExt	Helena	Aux Fan	613	16276	1410	187	18486	0.326	0.977	0.977
1stExt	Helena	Occupancy	601	16213	1349	165	18327	0.299	1.001	1.002
1stExt	Helena	Aux Fan + Occupancy	590	15528	1381	141	17641	0.268	0.992	0.993
1stExt	Helena	NULL Control	623	16893	1389	207	19112	0.353	0.984	0.984
1stExt	Duluth	No IAQ fan	565	16306	1151	14	18036	0.112	4.438	4.428
1stExt	Duluth	Continuous IAQ fan	658	21232	1060	221	23171	0.337	1.007	1.007
1stExt	Duluth	Aux Fan	662	21265	1078	183	23189	0.331	0.978	0.978
1stExt	Duluth	Occupancy	649	21003	1032	161	22845	0.306	1.000	1.001
1stExt	Duluth	Aux Fan + Occupancy	635	20215	1051	137	22038	0.274	0.991	0.992
1stExt	Duluth	NULL Control	674	21945	1061	202	23883	0.357	0.987	0.987
1stExt	Fairbanks	No IAQ fan	746	26057	881	14	27698	0.094	5.914	5.900
1stExt	Fairbanks	Continuous IAQ fan	897	33472	767	226	35362	0.341	1.003	1.003
1stExt	Fairbanks	Aux Fan	902	33586	781	193	35462	0.332	0.975	0.975
1stExt	Fairbanks	Occupancy	884	32929	765	172	34750	0.306	1.003	1.004
1stExt	Fairbanks	Aux Fan + Occupancy	863	31872	786	148	33669	0.274	0.993	0.994
1stExt	Fairbanks	NULL Control	922	34551	766	213	36452	0.360	0.980	0.981
3rd	Miami	No IAQ fan	1136	21	5053	14	6223	0.089	5.050	5.039
3rd	Miami	Continuous IAQ fan	1246	21	5873	224	7363	0.340	1.005	1.005
3rd	Miami	Aux Fan	1234	21	5794	188	7238	0.318	0.989	0.989
3rd	Miami	Occupancy	1244	21	5844	190	7299	0.323	1.001	1.002
3rd	Miami	Aux Fan + Occupancy	1232	21	5758	171	7182	0.296	0.995	0.995
3rd	Miami	NULL Control	1244	21	5865	208	7338	0.345	0.996	0.996
3rd	Houston	No IAQ fan	874	3909	3513	14	8311	0.099	4.930	4.919
3rd	Houston	Continuous IAQ fan	966	4823	4052	223	10064	0.340	1.005	1.005
3rd	Houston	Aux Fan	957	4780	3997	187	9921	0.322	0.989	0.989
3rd	Houston	Occupancy	967	4813	4041	189	10010	0.327	1.002	1.002
3rd	Houston	Aux Fan + Occupancy	957	4712	3987	170	9825	0.301	0.995	0.995
3rd	Houston	NULL Control	967	4911	4045	207	10130	0.349	0.997	0.997
3rd	Phoenix	No IAQ fan	1264	2229	5262	14	8769	0.083	4.816	4.805
3rd	Phoenix	Continuous	1353	3020	5613	223	10209	0.337	1.006	1.006

		IAQ fan								
3rd	Phoenix	Aux Fan	1345	2937	5582	187	10051	0.312	0.988	0.989
3rd	Phoenix	Occupancy	1348	2971	5593	189	10101	0.317	1.000	1.001
3rd	Phoenix	Aux Fan + Occupancy	1337	2911	5549	169	9965	0.290	0.994	0.995
3rd	Phoenix	NULL Control	1354	3047	5616	207	10224	0.340	0.996	0.996
3rd	Memphis	No IAQ fan	782	5956	3337	14	10089	0.102	5.401	5.389
3rd	Memphis	Continuous IAQ fan	868	7721	3759	225	12573	0.343	1.004	1.004
3rd	Memphis	Aux Fan	863	7710	3716	190	12480	0.327	0.988	0.988
3rd	Memphis	Occupancy	872	7713	3770	192	12548	0.333	1.002	1.002
3rd	Memphis	Aux Fan + Occupancy	861	7517	3721	173	12272	0.307	0.995	0.995
3rd	Memphis	NULL Control	872	7930	3753	210	12765	0.355	0.995	0.995
3rd	El Paso	No IAQ fan	780	3245	3573	14	7612	0.093	5.176	5.165
3rd	El Paso	Continuous IAQ fan	840	4787	3761	224	9612	0.340	1.005	1.005
3rd	El Paso	Aux Fan	836	4699	3741	189	9465	0.320	0.988	0.988
3rd	El Paso	Occupancy	843	4725	3777	191	9536	0.327	1.001	1.001
3rd	El Paso	Aux Fan + Occupancy	835	4569	3751	171	9326	0.300	0.995	0.995
3rd	El Paso	NULL Control	842	4899	3754	209	9704	0.348	0.995	0.995
3rd	San Francisco	No IAQ fan	256	2582	1013	14	3864	0.107	4.142	4.134
3rd	San Francisco	Continuous IAQ fan	258	4158	839	220	5474	0.334	1.009	1.009
3rd	San Francisco	Aux Fan	257	4012	852	182	5304	0.319	0.988	0.988
3rd	San Francisco	Occupancy	260	4016	868	183	5328	0.324	1.000	1.000
3rd	San Francisco	Aux Fan + Occupancy	259	3846	881	163	5150	0.298	0.993	0.994
3rd	San Francisco	NULL Control	259	4236	834	202	5531	0.346	0.995	0.996
3rd	Baltimore	No IAQ fan	652	9734	2214	14	12614	0.104	4.969	4.959
3rd	Baltimore	Continuous IAQ fan	731	12468	2407	223	15830	0.340	1.005	1.005
3rd	Baltimore	Aux Fan	728	12391	2386	188	15692	0.325	0.989	0.989
3rd	Baltimore	Occupancy	735	12426	2423	190	15774	0.331	1.001	1.001
3rd	Baltimore	Aux Fan + Occupancy	725	12134	2398	170	15427	0.305	0.995	0.995
3rd	Baltimore	NULL Control	737	12752	2401	207	16098	0.352	0.997	0.997
3rd	Albuquerque	No IAQ fan	648	7220	2436	14	10318	0.106	4.602	4.592
3rd	Albuquerque	Continuous IAQ fan	709	9762	2480	222	13173	0.338	1.007	1.007
3rd	Albuquerque	Aux Fan	706	9648	2473	186	13013	0.324	0.987	0.987
3rd	Albuquerque	Occupancy	712	9685	2505	187	13090	0.330	1.000	1.000
3rd	Albuquerque	Aux Fan + Occupancy	705	9418	2493	167	12783	0.303	0.994	0.994

3rd	Albuquerque	NULL Control	714	10000	2476	206	13396	0.351	0.993	0.993
3rd	Salem	No IAQ fan	458	6517	1838	14	8826	0.116	4.518	4.509
3rd	Salem	Continuous IAQ fan	488	8939	1708	222	11357	0.340	1.007	1.007
3rd	Salem	Aux Fan	489	8870	1717	185	11261	0.329	0.987	0.987
3rd	Salem	Occupancy	493	8879	1745	186	11304	0.334	1.000	1.000
3rd	Salem	Aux Fan + Occupancy	489	8621	1755	167	11032	0.308	0.994	0.994
3rd	Salem	NULL Control	494	9211	1703	205	11612	0.356	0.994	0.994
3rd	Chicago	No IAQ fan	647	11198	2358	14	14217	0.105	5.176	5.165
3rd	Chicago	Continuous IAQ fan	727	14728	2447	224	18126	0.341	1.005	1.005
3rd	Chicago	Aux Fan	725	14647	2437	189	17998	0.327	0.988	0.988
3rd	Chicago	Occupancy	733	14683	2482	191	18088	0.334	1.001	1.001
3rd	Chicago	Aux Fan + Occupancy	722	14286	2465	171	17645	0.307	0.995	0.995
3rd	Chicago	NULL Control	735	15098	2444	209	18487	0.355	0.995	0.995
3rd	Boise	No IAQ fan	575	7843	2322	14	10755	0.091	5.545	5.533
3rd	Boise	Continuous IAQ fan	629	11029	2197	225	14080	0.340	1.004	1.004
3rd	Boise	Aux Fan	627	10827	2212	191	13857	0.322	0.988	0.988
3rd	Boise	Occupancy	630	10870	2226	193	13919	0.327	1.002	1.002
3rd	Boise	Aux Fan + Occupancy	624	10536	2233	173	13567	0.301	0.995	0.995
3rd	Boise	NULL Control	633	11220	2193	211	14257	0.350	0.994	0.994
3rd	Burlington	No IAQ fan	584	12558	1768	14	14923	0.111	5.091	5.080
3rd	Burlington	Continuous IAQ fan	664	16510	1760	224	19158	0.341	1.005	1.005
3rd	Burlington	Aux Fan	664	16448	1763	188	19063	0.330	0.988	0.988
3rd	Burlington	Occupancy	669	16520	1788	191	19168	0.337	1.001	1.001
3rd	Burlington	Aux Fan + Occupancy	659	16070	1786	171	18685	0.310	0.995	0.995
3rd	Burlington	NULL Control	674	16967	1759	208	19609	0.357	0.995	0.995
3rd	Helena	No IAQ fan	535	12024	1528	14	14101	0.097	4.930	4.919
3rd	Helena	Continuous IAQ fan	613	16396	1398	223	18631	0.337	1.005	1.005
3rd	Helena	Aux Fan	610	16147	1410	187	18354	0.320	0.989	0.989
3rd	Helena	Occupancy	614	16237	1425	189	18465	0.326	1.002	1.002
3rd	Helena	Aux Fan + Occupancy	605	15751	1434	170	17960	0.300	0.995	0.995
3rd	Helena	NULL Control	620	16711	1396	207	18935	0.347	0.997	0.997
3rd	Duluth	No IAQ fan	565	16277	1159	14	18015	0.112	4.438	4.428
3rd	Duluth	Continuous IAQ fan	659	21208	1069	221	23157	0.337	1.007	1.007

3rd	Duluth	Aux Fan	658	21095	1079	185	23018	0.325	0.988	0.988
3rd	Duluth	Occupancy	663	21181	1096	186	23127	0.331	1.000	1.000
3rd	Duluth	Aux Fan + Occupancy	651	20595	1103	166	22515	0.304	0.994	0.994
3rd	Duluth	NULL Control	671	21725	1070	204	23670	0.352	0.995	0.995
3rd	Fairbanks	No IAQ fan	746	26017	882	14	27658	0.094	5.914	5.900
3rd	Fairbanks	Continuous IAQ fan	897	33454	769	226	35346	0.341	1.003	1.003
3rd	Fairbanks	Aux Fan	894	33231	781	192	35098	0.325	0.989	0.989
3rd	Fairbanks	Occupancy	898	33370	784	195	35247	0.333	1.002	1.003
3rd	Fairbanks	Aux Fan + Occupancy	881	32554	794	175	34404	0.306	0.996	0.996
3rd	Fairbanks	NULL Control	913	34150	769	212	36044	0.353	0.996	0.996

Table 16 Full AEQ, unbalanced IAQ fans. Annual data summary, organized by climate zone and occupancy pattern.

Occupancy	CZ	Control	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mechanical Ventilation (kWh/yr)	Total (kWh/yr)	Air Exchange Rate (hr^{-1})	Avg Relative Exposure	Avg Relative Dose
1st	Miami	No IAQ fan	1135	21	5049	14	6219	0.089	5.050	5.039
1st	Miami	Continuous IAQ fan	1245	21	5865	224	7355	0.340	1.005	1.005
1st	Miami	Aux Fan	1236	21	5800	188	7245	0.317	0.989	0.989
1st	Miami	Occupancy	1211	21	5650	169	7051	0.296	0.996	0.996
1st	Miami	NULL Control	1243	21	5858	208	7330	0.345	0.996	0.996
1st	Miami	Aux Fan + Occupancy	1202	21	5588	149	6961	0.268	0.989	0.989
1st	Houston	No IAQ fan	874	3910	3510	14	8309	0.099	4.930	4.919
1st	Houston	Continuous IAQ fan	966	4806	4052	223	10048	0.340	1.005	1.005
1st	Houston	Aux Fan	958	4773	3999	187	9917	0.322	0.989	0.989
1st	Houston	Occupancy	941	4771	3902	169	9783	0.301	0.996	0.996
1st	Houston	NULL Control	966	4883	4042	207	10097	0.349	0.997	0.997
1st	Houston	Aux Fan + Occupancy	932	4660	3857	148	9598	0.273	0.989	0.990
1st	Phoenix	No IAQ fan	1268	2203	5280	14	8765	0.083	4.816	4.805
1st	Phoenix	Continuous IAQ fan	1356	2993	5626	223	10197	0.337	1.006	1.006
1st	Phoenix	Aux Fan	1346	2928	5588	187	10049	0.312	0.988	0.988
1st	Phoenix	Occupancy	1333	2912	5522	168	9935	0.288	0.995	0.995
1st	Phoenix	NULL Control	1358	3023	5631	207	10219	0.339	0.996	0.996
1st	Phoenix	Aux Fan + Occupancy	1320	2810	5477	148	9755	0.260	0.990	0.990
1st	Memphis	No IAQ fan	781	5954	3334	14	10083	0.102	5.401	5.389
1st	Memphis	Continuous IAQ fan	868	7722	3756	225	12570	0.343	1.004	1.004
1st	Memphis	Aux Fan	863	7688	3719	190	12459	0.327	0.988	0.988
1st	Memphis	Occupancy	849	7645	3630	171	12295	0.307	0.995	0.995
1st	Memphis	NULL Control	871	7924	3749	210	12754	0.355	0.995	0.995
1st	Memphis	Aux Fan + Occupancy	840	7407	3598	151	11996	0.279	0.989	0.989
1st	El Paso	No IAQ fan	782	3223	3578	14	7597	0.093	5.176	5.165
1st	El Paso	Continuous IAQ fan	842	4765	3768	224	9599	0.340	1.005	1.005
1st	El Paso	Aux Fan	837	4679	3746	189	9451	0.320	0.988	0.988
1st	El Paso	Occupancy	826	4698	3679	170	9373	0.298	0.995	0.995
1st	El Paso	NULL Control	843	4886	3761	209	9699	0.348	0.995	0.995
1st	El Paso	Aux Fan + Occupancy	819	4506	3661	150	9136	0.270	0.989	0.989

1st	San Francisco	No IAQ fan	256	2588	1011	14	3869	0.106	4.142	4.134
1st	San Francisco	Continuous IAQ fan	257	4167	836	220	5479	0.334	1.009	1.009
1st	San Francisco	Aux Fan	257	4013	853	182	5306	0.318	0.988	0.988
1st	San Francisco	Occupancy	255	4003	844	163	5265	0.296	0.996	0.996
1st	San Francisco	NULL Control	259	4243	832	202	5536	0.345	0.995	0.996
1st	San Francisco	Aux Fan + Occupancy	254	3776	866	142	5038	0.269	0.991	0.991
1st	Baltimore	No IAQ fan	652	9723	2215	14	12605	0.104	4.969	4.959
1st	Baltimore	Continuous IAQ fan	732	12463	2407	223	15825	0.340	1.005	1.005
1st	Baltimore	Aux Fan	728	12393	2389	188	15698	0.325	0.989	0.989
1st	Baltimore	Occupancy	717	12278	2329	169	15493	0.304	0.996	0.996
1st	Baltimore	NULL Control	737	12736	2401	207	16082	0.352	0.997	0.997
1st	Baltimore	Aux Fan + Occupancy	707	11924	2312	149	15091	0.276	0.990	0.990
1st	Albuquerque	No IAQ fan	648	7202	2435	14	10299	0.106	4.602	4.592
1st	Albuquerque	Continuous IAQ fan	709	9725	2481	222	13137	0.338	1.007	1.007
1st	Albuquerque	Aux Fan	706	9616	2477	186	12985	0.324	0.987	0.987
1st	Albuquerque	Occupancy	697	9607	2428	166	12898	0.301	0.995	0.995
1st	Albuquerque	NULL Control	714	9981	2478	206	13379	0.351	0.993	0.993
1st	Albuquerque	Aux Fan + Occupancy	689	9273	2424	146	12532	0.273	0.990	0.990
1st	Salem	No IAQ fan	458	6518	1842	14	8832	0.116	4.518	4.509
1st	Salem	Continuous IAQ fan	489	8946	1713	222	11370	0.340	1.007	1.007
1st	Salem	Aux Fan	489	8844	1720	185	11238	0.329	0.987	0.987
1st	Salem	Occupancy	485	8758	1708	166	11117	0.307	0.995	0.995
1st	Salem	NULL Control	494	9204	1707	205	11611	0.356	0.994	0.994
1st	Salem	Aux Fan + Occupancy	479	8431	1718	145	10774	0.280	0.990	0.990
1st	Chicago	No IAQ fan	647	11195	2352	14	14208	0.105	5.176	5.165
1st	Chicago	Continuous IAQ fan	727	14741	2442	224	18135	0.341	1.005	1.005
1st	Chicago	Aux Fan	726	14645	2439	189	17999	0.327	0.988	0.988
1st	Chicago	Occupancy	715	14484	2378	170	17746	0.306	0.995	0.995
1st	Chicago	NULL Control	735	15099	2440	209	18484	0.355	0.995	0.995
1st	Chicago	Aux Fan + Occupancy	705	14027	2374	150	17255	0.279	0.989	0.989
1st	Boise	No IAQ fan	577	7816	2338	14	10746	0.091	5.545	5.533
1st	Boise	Continuous IAQ fan	631	11002	2212	225	14071	0.340	1.004	1.004
1st	Boise	Aux Fan	627	10805	2215	191	13839	0.322	0.988	0.988
1st	Boise	Occupancy	623	10656	2207	172	13658	0.299	0.995	0.995

1st	Boise	NULL Control	635	11192	2208	211	14246	0.350	0.994	0.994
1st	Boise	Aux Fan + Occupancy	614	10272	2211	152	13250	0.271	0.989	0.989
1st	Burlington	No IAQ fan	584	12556	1770	14	14924	0.112	5.091	5.080
1st	Burlington	Continuous IAQ fan	665	16520	1763	224	19173	0.341	1.005	1.005
1st	Burlington	Aux Fan	664	16435	1765	188	19053	0.330	0.988	0.988
1st	Burlington	Occupancy	655	16215	1736	169	18776	0.310	0.996	0.996
1st	Burlington	NULL Control	675	16962	1761	208	19606	0.358	0.995	0.995
1st	Burlington	Aux Fan + Occupancy	645	15706	1739	149	18239	0.283	0.989	0.989
1st	Helena	No IAQ fan	535	11987	1535	14	14071	0.097	4.930	4.919
1st	Helena	Continuous IAQ fan	613	16347	1405	223	18589	0.337	1.005	1.005
1st	Helena	Aux Fan	610	16125	1414	187	18336	0.320	0.989	0.989
1st	Helena	Occupancy	603	15893	1405	169	18070	0.298	0.996	0.996
1st	Helena	NULL Control	621	16679	1404	207	18910	0.347	0.997	0.997
1st	Helena	Aux Fan + Occupancy	593	15348	1416	148	17505	0.270	0.989	0.990
1st	Duluth	No IAQ fan	565	16256	1160	14	17995	0.112	4.438	4.428
1st	Duluth	Continuous IAQ fan	658	21190	1069	221	23139	0.337	1.007	1.007
1st	Duluth	Aux Fan	658	21073	1081	185	22997	0.325	0.988	0.988
1st	Duluth	Occupancy	649	20730	1068	165	22613	0.303	0.995	0.995
1st	Duluth	NULL Control	671	21718	1070	204	23664	0.352	0.995	0.995
1st	Duluth	Aux Fan + Occupancy	636	20075	1078	145	21934	0.276	0.990	0.990
1st	Fairbanks	No IAQ fan	746	25987	886	14	27632	0.094	5.914	5.900
1st	Fairbanks	Continuous IAQ fan	897	33416	772	226	35311	0.341	1.003	1.003
1st	Fairbanks	Aux Fan	894	33237	783	192	35106	0.325	0.989	0.989
1st	Fairbanks	Occupancy	881	32627	790	174	34472	0.304	0.995	0.996
1st	Fairbanks	NULL Control	913	34114	772	212	36011	0.353	0.996	0.996
1st	Fairbanks	Aux Fan + Occupancy	863	31740	800	154	33556	0.276	0.989	0.989
1stExt	Miami	No IAQ fan	1132	21	5038	14	6204	0.090	5.050	5.039
1stExt	Miami	Continuous IAQ fan	1241	21	5847	224	7333	0.341	1.005	1.005
1stExt	Miami	Aux Fan	1235	21	5801	188	7245	0.322	0.977	0.977
1stExt	Miami	Occupancy	1182	21	5480	139	6822	0.257	0.997	0.997
1stExt	Miami	NULL Control	1241	21	5847	207	7316	0.350	0.985	0.985
1stExt	Miami	Aux Fan + Occupancy	1176	21	5422	117	6735	0.227	0.990	0.990
1stExt	Houston	No IAQ fan	871	3936	3495	14	8315	0.100	4.930	4.919

1stExt	Houston	Continuous IAQ fan	962	4839	4028	223	10052	0.341	1.005	1.005
1stExt	Houston	Aux Fan	959	4811	4003	187	9959	0.328	0.977	0.977
1stExt	Houston	Occupancy	915	4721	3759	138	9532	0.263	0.998	0.998
1stExt	Houston	NULL Control	964	4953	4026	207	10150	0.355	0.984	0.984
1stExt	Houston	Aux Fan + Occupancy	909	4568	3729	116	9321	0.233	0.990	0.990
1stExt	Phoenix	No IAQ fan	1263	2236	5257	14	8769	0.084	4.816	4.805
1stExt	Phoenix	Continuous IAQ fan	1350	3008	5603	223	10184	0.337	1.006	1.006
1stExt	Phoenix	Aux Fan	1347	2952	5592	186	10077	0.315	0.978	0.978
1stExt	Phoenix	Occupancy	1299	2890	5381	137	9707	0.250	0.997	0.997
1stExt	Phoenix	NULL Control	1354	3061	5613	205	10234	0.343	0.986	0.986
1stExt	Phoenix	Aux Fan + Occupancy	1294	2762	5364	115	9536	0.219	0.990	0.990
1stExt	Memphis	No IAQ fan	779	5989	3318	14	10100	0.103	5.401	5.389
1stExt	Memphis	Continuous IAQ fan	865	7751	3736	225	12576	0.343	1.004	1.004
1stExt	Memphis	Aux Fan	864	7757	3717	190	12527	0.333	0.977	0.977
1stExt	Memphis	Occupancy	825	7445	3506	141	11917	0.269	0.997	0.997
1stExt	Memphis	NULL Control	870	8026	3730	209	12835	0.360	0.985	0.985
1stExt	Memphis	Aux Fan + Occupancy	818	7151	3489	119	11577	0.239	0.990	0.990
1stExt	El Paso	No IAQ fan	778	3275	3557	14	7624	0.093	5.176	5.165
1stExt	El Paso	Continuous IAQ fan	838	4814	3744	224	9621	0.340	1.005	1.005
1stExt	El Paso	Aux Fan	837	4731	3742	188	9498	0.325	0.978	0.978
1stExt	El Paso	Occupancy	804	4605	3574	139	9123	0.259	0.997	0.997
1stExt	El Paso	NULL Control	841	4966	3740	208	9754	0.352	0.987	0.987
1stExt	El Paso	Aux Fan + Occupancy	800	4321	3579	117	8817	0.229	0.990	0.990
1stExt	San Francisco	No IAQ fan	255	2612	1005	14	3887	0.107	4.142	4.134
1stExt	San Francisco	Continuous IAQ fan	258	4209	831	220	5518	0.334	1.009	1.009
1stExt	San Francisco	Aux Fan	257	4041	850	181	5330	0.324	0.976	0.976
1stExt	San Francisco	Occupancy	254	3819	860	132	5065	0.260	0.997	0.997
1stExt	San Francisco	NULL Control	259	4317	825	201	5601	0.351	0.983	0.983
1stExt	San Francisco	Aux Fan + Occupancy	253	3533	888	110	4785	0.231	0.991	0.991
1stExt	Baltimore	No IAQ fan	651	9775	2200	14	12639	0.105	4.969	4.959
1stExt	Baltimore	Continuous IAQ fan	730	12511	2391	223	15855	0.340	1.005	1.005
1stExt	Baltimore	Aux Fan	730	12488	2387	187	15792	0.331	0.977	0.977
1stExt	Baltimore	Occupancy	696	11938	2247	138	15019	0.267	0.997	0.997
1stExt	Baltimore	NULL	737	12876	2385	207	16205	0.358	0.984	0.984

		Control								
1stExt	Baltimore	Aux Fan + Occupancy	689	11527	2248	116	14580	0.237	0.990	0.990
1stExt	Albuquerque	No IAQ fan	646	7256	2423	14	10338	0.107	4.602	4.592
1stExt	Albuquerque	Continuous IAQ fan	707	9805	2464	222	13197	0.338	1.007	1.007
1stExt	Albuquerque	Aux Fan	708	9706	2474	184	13072	0.329	0.978	0.979
1stExt	Albuquerque	Occupancy	680	9410	2369	136	12596	0.265	0.996	0.997
1stExt	Albuquerque	NULL Control	714	10103	2462	204	13483	0.355	0.986	0.986
1stExt	Albuquerque	Aux Fan + Occupancy	673	8957	2380	114	12123	0.235	0.990	0.991
1stExt	Salem	No IAQ fan	456	6564	1824	14	8858	0.117	4.518	4.509
1stExt	Salem	Continuous IAQ fan	487	8988	1692	222	11389	0.340	1.007	1.007
1stExt	Salem	Aux Fan	491	8964	1715	184	11354	0.334	0.979	0.979
1stExt	Salem	Occupancy	473	8481	1669	135	10758	0.271	0.997	0.997
1stExt	Salem	NULL Control	494	9310	1688	203	11694	0.360	0.988	0.988
1stExt	Salem	Aux Fan + Occupancy	470	8085	1703	113	10371	0.242	0.990	0.991
1stExt	Chicago	No IAQ fan	645	11243	2337	14	14240	0.106	5.176	5.165
1stExt	Chicago	Continuous IAQ fan	726	14776	2427	224	18152	0.341	1.005	1.005
1stExt	Chicago	Aux Fan	728	14782	2437	188	18135	0.333	0.978	0.978
1stExt	Chicago	Occupancy	695	13999	2314	139	17148	0.269	0.997	0.997
1stExt	Chicago	NULL Control	736	15247	2425	208	18616	0.360	0.987	0.987
1stExt	Chicago	Aux Fan + Occupancy	687	13489	2324	117	16617	0.240	0.990	0.990
1stExt	Boise	No IAQ fan	574	7866	2315	14	10769	0.091	5.545	5.533
1stExt	Boise	Continuous IAQ fan	628	11042	2188	225	14083	0.340	1.004	1.004
1stExt	Boise	Aux Fan	628	10888	2211	190	13918	0.327	0.977	0.977
1stExt	Boise	Occupancy	604	10327	2146	141	13218	0.261	0.998	0.998
1stExt	Boise	NULL Control	633	11306	2184	210	14333	0.354	0.984	0.984
1stExt	Boise	Aux Fan + Occupancy	598	9871	2174	119	12763	0.231	0.990	0.990
1stExt	Burlington	No IAQ fan	583	12603	1757	14	14957	0.112	5.091	5.080
1stExt	Burlington	Continuous IAQ fan	663	16559	1749	224	19195	0.341	1.005	1.005
1stExt	Burlington	Aux Fan	667	16604	1762	188	19221	0.337	0.978	0.978
1stExt	Burlington	Occupancy	637	15658	1694	139	18127	0.273	0.998	0.998
1stExt	Burlington	NULL Control	677	17154	1747	207	19786	0.364	0.986	0.986
1stExt	Burlington	Aux Fan + Occupancy	627	15091	1710	117	17544	0.244	0.990	0.990
1stExt	Helena	No IAQ fan	534	12046	1521	14	14116	0.097	4.930	4.919
1stExt	Helena	Continuous	613	16418	1391	223	18645	0.338	1.005	1.005

		IAQ fan								
1stExt	Helena	Aux Fan	613	16276	1410	187	18486	0.326	0.977	0.977
1stExt	Helena	Occupancy	587	15388	1380	138	17493	0.260	0.998	0.998
1stExt	Helena	NULL Control	623	16893	1389	207	19112	0.353	0.984	0.984
1stExt	Helena	Aux Fan + Occupancy	577	14746	1406	116	16844	0.230	0.990	0.990
1stExt	Duluth	No IAQ fan	565	16306	1151	14	18036	0.112	4.438	4.428
1stExt	Duluth	Continuous IAQ fan	658	21232	1060	221	23171	0.337	1.007	1.007
1stExt	Duluth	Aux Fan	662	21265	1078	183	23189	0.331	0.978	0.978
1stExt	Duluth	Occupancy	631	20013	1053	134	21831	0.267	0.997	0.997
1stExt	Duluth	NULL Control	674	21945	1061	202	23883	0.357	0.987	0.987
1stExt	Duluth	Aux Fan + Occupancy	618	19293	1075	112	21099	0.237	0.991	0.991
1stExt	Fairbanks	No IAQ fan	746	26057	881	14	27698	0.094	5.914	5.900
1stExt	Fairbanks	Continuous IAQ fan	897	33472	767	226	35362	0.341	1.003	1.003
1stExt	Fairbanks	Aux Fan	902	33586	781	193	35462	0.332	0.975	0.975
1stExt	Fairbanks	Occupancy	856	31558	787	143	33345	0.265	0.998	0.998
1stExt	Fairbanks	NULL Control	922	34551	766	213	36452	0.360	0.980	0.981
1stExt	Fairbanks	Aux Fan + Occupancy	837	30598	804	121	32361	0.236	0.990	0.991
3rd	Miami	No IAQ fan	1136	21	5053	14	6223	0.089	5.050	5.039
3rd	Miami	Continuous IAQ fan	1246	21	5873	224	7363	0.340	1.005	1.005
3rd	Miami	Aux Fan	1234	21	5794	188	7238	0.318	0.989	0.989
3rd	Miami	Occupancy	1234	21	5770	170	7195	0.294	0.996	0.996
3rd	Miami	NULL Control	1244	21	5865	208	7338	0.345	0.996	0.996
3rd	Miami	Aux Fan + Occupancy	1224	21	5696	149	7091	0.266	0.991	0.991
3rd	Houston	No IAQ fan	874	3909	3513	14	8311	0.099	4.930	4.919
3rd	Houston	Continuous IAQ fan	966	4823	4052	223	10064	0.340	1.005	1.005
3rd	Houston	Aux Fan	957	4780	3997	187	9921	0.322	0.989	0.989
3rd	Houston	Occupancy	958	4679	3996	169	9802	0.300	0.996	0.997
3rd	Houston	NULL Control	967	4911	4045	207	10130	0.349	0.997	0.997
3rd	Houston	Aux Fan + Occupancy	950	4547	3952	148	9597	0.272	0.991	0.991
3rd	Phoenix	No IAQ fan	1264	2229	5262	14	8769	0.083	4.816	4.805
3rd	Phoenix	Continuous IAQ fan	1353	3020	5613	223	10209	0.337	1.006	1.006
3rd	Phoenix	Aux Fan	1345	2937	5582	187	10051	0.312	0.988	0.989
3rd	Phoenix	Occupancy	1340	2864	5566	168	9937	0.288	0.996	0.996
3rd	Phoenix	NULL Control	1354	3047	5616	207	10224	0.340	0.996	0.996

3rd	Phoenix	Aux Fan + Occupancy	1332	2736	5538	148	9754	0.260	0.991	0.991
3rd	Memphis	No IAQ fan	782	5956	3337	14	10089	0.102	5.401	5.389
3rd	Memphis	Continuous IAQ fan	868	7721	3759	225	12573	0.343	1.004	1.004
3rd	Memphis	Aux Fan	863	7710	3716	190	12480	0.327	0.988	0.988
3rd	Memphis	Occupancy	863	7486	3735	171	12255	0.306	0.996	0.996
3rd	Memphis	NULL Control	872	7930	3753	210	12765	0.355	0.995	0.995
3rd	Memphis	Aux Fan + Occupancy	854	7263	3699	151	11967	0.278	0.990	0.990
3rd	El Paso	No IAQ fan	780	3245	3573	14	7612	0.093	5.176	5.165
3rd	El Paso	Continuous IAQ fan	840	4787	3761	224	9612	0.340	1.005	1.005
3rd	El Paso	Aux Fan	836	4699	3741	189	9465	0.320	0.988	0.988
3rd	El Paso	Occupancy	837	4542	3762	170	9311	0.298	0.996	0.996
3rd	El Paso	NULL Control	842	4899	3754	209	9704	0.348	0.995	0.995
3rd	El Paso	Aux Fan + Occupancy	831	4309	3751	150	9041	0.271	0.990	0.991
3rd	San Francisco	No IAQ fan	256	2582	1013	14	3864	0.107	4.142	4.134
3rd	San Francisco	Continuous IAQ fan	258	4158	839	220	5474	0.334	1.009	1.009
3rd	San Francisco	Aux Fan	257	4012	852	182	5304	0.319	0.988	0.988
3rd	San Francisco	Occupancy	259	3801	886	163	5109	0.297	0.996	0.997
3rd	San Francisco	NULL Control	259	4236	834	202	5531	0.346	0.995	0.996
3rd	San Francisco	Aux Fan + Occupancy	258	3592	906	143	4898	0.269	0.991	0.991
3rd	Baltimore	No IAQ fan	652	9734	2214	14	12614	0.104	4.969	4.959
3rd	Baltimore	Continuous IAQ fan	731	12468	2407	223	15830	0.340	1.005	1.005
3rd	Baltimore	Aux Fan	728	12391	2386	188	15692	0.325	0.989	0.989
3rd	Baltimore	Occupancy	725	12087	2404	169	15385	0.304	0.996	0.997
3rd	Baltimore	NULL Control	737	12752	2401	207	16098	0.352	0.997	0.997
3rd	Baltimore	Aux Fan + Occupancy	716	11735	2389	149	14989	0.276	0.991	0.991
3rd	Albuquerque	No IAQ fan	648	7220	2436	14	10318	0.106	4.602	4.592
3rd	Albuquerque	Continuous IAQ fan	709	9762	2480	222	13173	0.338	1.007	1.007
3rd	Albuquerque	Aux Fan	706	9648	2473	186	13013	0.324	0.987	0.987
3rd	Albuquerque	Occupancy	705	9330	2504	167	12706	0.302	0.996	0.996
3rd	Albuquerque	NULL Control	714	10000	2476	206	13396	0.351	0.993	0.993
3rd	Albuquerque	Aux Fan + Occupancy	698	8973	2503	146	12320	0.274	0.991	0.991
3rd	Salem	No IAQ fan	458	6517	1838	14	8826	0.116	4.518	4.509
3rd	Salem	Continuous IAQ fan	488	8939	1708	222	11357	0.340	1.007	1.007

3rd	Salem	Aux Fan	489	8870	1717	185	11261	0.329	0.987	0.987
3rd	Salem	Occupancy	490	8563	1770	166	10989	0.307	0.996	0.996
3rd	Salem	NULL Control	494	9211	1703	205	11612	0.356	0.994	0.994
3rd	Salem	Aux Fan + Occupancy	486	8233	1787	146	10652	0.280	0.991	0.991
3rd	Chicago	No IAQ fan	647	11198	2358	14	14217	0.105	5.176	5.165
3rd	Chicago	Continuous IAQ fan	727	14728	2447	224	18126	0.341	1.005	1.005
3rd	Chicago	Aux Fan	725	14647	2437	189	17998	0.327	0.988	0.988
3rd	Chicago	Occupancy	722	14276	2467	170	17636	0.306	0.996	0.996
3rd	Chicago	NULL Control	735	15098	2444	209	18487	0.355	0.995	0.995
3rd	Chicago	Aux Fan + Occupancy	712	13827	2458	150	17147	0.278	0.990	0.991
3rd	Boise	No IAQ fan	575	7843	2322	14	10755	0.091	5.545	5.533
3rd	Boise	Continuous IAQ fan	629	11029	2197	225	14080	0.340	1.004	1.004
3rd	Boise	Aux Fan	627	10827	2212	191	13857	0.322	0.988	0.988
3rd	Boise	Occupancy	624	10476	2243	172	13515	0.300	0.996	0.996
3rd	Boise	NULL Control	633	11220	2193	211	14257	0.350	0.994	0.994
3rd	Boise	Aux Fan + Occupancy	618	10067	2260	152	13097	0.271	0.990	0.990
3rd	Burlington	No IAQ fan	584	12558	1768	14	14923	0.111	5.091	5.080
3rd	Burlington	Continuous IAQ fan	664	16510	1760	224	19158	0.341	1.005	1.005
3rd	Burlington	Aux Fan	664	16448	1763	188	19063	0.330	0.988	0.988
3rd	Burlington	Occupancy	659	16025	1791	170	18645	0.309	0.996	0.996
3rd	Burlington	NULL Control	674	16967	1759	208	19609	0.357	0.995	0.995
3rd	Burlington	Aux Fan + Occupancy	649	15520	1794	149	18112	0.282	0.991	0.991
3rd	Helena	No IAQ fan	535	12024	1528	14	14101	0.097	4.930	4.919
3rd	Helena	Continuous IAQ fan	613	16396	1398	223	18631	0.337	1.005	1.005
3rd	Helena	Aux Fan	610	16147	1410	187	18354	0.320	0.989	0.989
3rd	Helena	Occupancy	604	15681	1443	169	17897	0.298	0.996	0.997
3rd	Helena	NULL Control	620	16711	1396	207	18935	0.347	0.997	0.997
3rd	Helena	Aux Fan + Occupancy	595	15110	1461	148	17313	0.270	0.991	0.991
3rd	Duluth	No IAQ fan	565	16277	1159	14	18015	0.112	4.438	4.428
3rd	Duluth	Continuous IAQ fan	659	21208	1069	221	23157	0.337	1.007	1.007
3rd	Duluth	Aux Fan	658	21095	1079	185	23018	0.325	0.988	0.988
3rd	Duluth	Occupancy	650	20528	1107	165	22451	0.303	0.996	0.996
3rd	Duluth	NULL Control	671	21725	1070	204	23670	0.352	0.995	0.995
3rd	Duluth	Aux Fan +	638	19894	1117	145	21794	0.276	0.991	0.991

		Occupancy								
3rd	Fairbanks	No IAQ fan	746	26017	882	14	27658	0.094	5.914	5.900
3rd	Fairbanks	Continuous IAQ fan	897	33454	769	226	35346	0.341	1.003	1.003
3rd	Fairbanks	Aux Fan	894	33231	781	192	35098	0.325	0.989	0.989
3rd	Fairbanks	Occupancy	880	32486	798	174	34338	0.304	0.996	0.996
3rd	Fairbanks	NULL Control	913	34150	769	212	36044	0.353	0.996	0.996
3rd	Fairbanks	Aux Fan + Occupancy	862	31589	812	154	33416	0.276	0.990	0.990

Table 17 Half AEQ, unbalanced IAQ fans. Annual data summary, organized by climate zone and occupancy pattern.

Occupancy	CZ	Control	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mechanical Ventilation (kWh/yr)	Total (kWh/yr)	Air Exchange Rate (hr^{-1})	Avg Relative Exposure	Avg Relative Dose
1st	Miami	No IAQ fan	1135	21	5049	14	6219	0.089	5.050	5.039
1st	Miami	Continuous IAQ fan	1221	21	5754	189	7186	0.344	0.999	0.999
1st	Miami	Aux Fan	1214	21	5693	169	7096	0.314	0.991	0.991
1st	Miami	Occupancy	1203	21	5631	173	7028	0.320	1.006	1.006
1st	Miami	Aux Fan + Occupancy	1197	21	5578	154	6950	0.292	0.997	0.997
1st	Houston	No IAQ fan	874	3910	3510	14	8309	0.099	4.930	4.919
1st	Houston	Continuous IAQ fan	952	5042	3960	188	10142	0.353	0.999	0.999
1st	Houston	Aux Fan	944	4901	3919	168	9932	0.323	0.991	0.991
1st	Houston	Occupancy	937	5005	3871	172	9985	0.329	1.006	1.006
1st	Houston	Aux Fan + Occupancy	931	4867	3842	152	9793	0.301	0.996	0.997
1st	Phoenix	No IAQ fan	1268	2203	5280	14	8765	0.083	4.816	4.805
1st	Phoenix	Continuous IAQ fan	1339	3072	5545	187	10144	0.334	0.999	0.999
1st	Phoenix	Aux Fan	1329	2975	5505	166	9976	0.304	0.991	0.991
1st	Phoenix	Occupancy	1332	3045	5506	170	10054	0.310	1.006	1.007
1st	Phoenix	Aux Fan + Occupancy	1323	2938	5474	151	9886	0.282	0.996	0.996
1st	Memphis	No IAQ fan	781	5954	3334	14	10083	0.102	5.401	5.389
1st	Memphis	Continuous IAQ fan	863	8227	3665	192	12947	0.363	0.999	0.999
1st	Memphis	Aux Fan	853	7934	3636	171	12594	0.333	0.992	0.992
1st	Memphis	Occupancy	851	8117	3595	176	12738	0.340	1.007	1.007
1st	Memphis	Aux Fan + Occupancy	844	7854	3574	157	12428	0.311	0.998	0.998
1st	El Paso	No IAQ fan	782	3223	3578	14	7597	0.093	5.176	5.165
1st	El Paso	Continuous IAQ fan	831	5071	3676	190	9769	0.351	0.999	0.999
1st	El Paso	Aux Fan	824	4815	3665	170	9474	0.320	0.991	0.991
1st	El Paso	Occupancy	825	5015	3641	174	9655	0.327	1.006	1.007
1st	El Paso	Aux Fan + Occupancy	820	4791	3636	155	9402	0.299	0.997	0.997
1st	San Francisco	No IAQ fan	256	2588	1011	14	3869	0.106	4.142	4.134
1st	San Francisco	Continuous IAQ fan	255	4352	804	180	5590	0.349	0.999	0.999
1st	San Francisco	Aux Fan	254	4092	828	159	5333	0.320	0.990	0.990
1st	San	Occupancy	255	4289	808	163	5515	0.325	1.005	1.005

	Francisco									
1st	San Francisco	Aux Fan + Occupancy	254	4032	833	144	5262	0.297	0.995	0.996
1st	Baltimore	No IAQ fan	652	9723	2215	14	12605	0.104	4.969	4.958
1st	Baltimore	Continuous IAQ fan	735	13145	2338	188	16406	0.361	0.999	0.999
1st	Baltimore	Aux Fan	725	12727	2329	168	15949	0.331	0.991	0.991
1st	Baltimore	Occupancy	723	12895	2294	172	16084	0.337	1.006	1.007
1st	Baltimore	Aux Fan + Occupancy	716	12530	2293	153	15691	0.309	0.997	0.997
1st	Albuquerqu e	No IAQ fan	648	7202	2435	14	10299	0.106	4.602	4.592
1st	Albuquerqu e	Continuous IAQ fan	709	10302	2416	185	13612	0.358	0.999	0.999
1st	Albuquerqu e	Aux Fan	702	9919	2419	164	13204	0.328	0.991	0.991
1st	Albuquerqu e	Occupancy	703	10203	2390	168	13464	0.334	1.006	1.006
1st	Albuquerqu e	Aux Fan + Occupancy	696	9817	2396	149	13058	0.305	0.996	0.996
1st	Salem	No IAQ fan	458	6518	1842	14	8832	0.116	4.518	4.509
1st	Salem	Continuous IAQ fan	494	9556	1657	184	11892	0.367	0.999	0.999
1st	Salem	Aux Fan	489	9162	1677	164	11492	0.337	0.991	0.991
1st	Salem	Occupancy	490	9387	1656	168	11701	0.343	1.006	1.006
1st	Salem	Aux Fan + Occupancy	485	8986	1680	148	11299	0.314	0.996	0.996
1st	Chicago	No IAQ fan	647	11195	2352	14	14208	0.105	5.176	5.165
1st	Chicago	Continuous IAQ fan	738	15579	2389	190	18897	0.366	0.999	0.999
1st	Chicago	Aux Fan	728	15089	2391	170	18378	0.336	0.991	0.991
1st	Chicago	Occupancy	727	15324	2345	174	18570	0.342	1.006	1.007
1st	Chicago	Aux Fan + Occupancy	718	14820	2351	155	18044	0.314	0.997	0.997
1st	Boise	No IAQ fan	577	7816	2338	14	10746	0.091	5.545	5.532
1st	Boise	Continuous IAQ fan	634	11515	2158	193	14499	0.355	0.999	0.999
1st	Boise	Aux Fan	625	11055	2169	172	14021	0.324	0.992	0.992
1st	Boise	Occupancy	631	11340	2162	177	14309	0.331	1.007	1.007
1st	Boise	Aux Fan + Occupancy	624	10892	2183	158	13857	0.303	0.998	0.998
1st	Burlington	No IAQ fan	584	12556	1770	14	14924	0.112	5.091	5.080
1st	Burlington	Continuous IAQ fan	681	17579	1713	190	20162	0.373	0.999	0.999
1st	Burlington	Aux Fan	670	17008	1723	169	19570	0.342	0.991	0.991
1st	Burlington	Occupancy	671	17224	1698	173	19766	0.348	1.006	1.007
1st	Burlington	Aux Fan + Occupancy	661	16644	1710	154	19169	0.320	0.997	0.997
1st	Helena	No IAQ fan	535	11987	1535	14	14071	0.097	4.930	4.919
1st	Helena	Continuous IAQ fan	625	17153	1365	188	19331	0.355	0.999	0.999

1st	Helena	Aux Fan	614	16553	1380	168	18715	0.325	0.991	0.991
1st	Helena	Occupancy	618	16823	1365	172	18977	0.331	1.006	1.006
1st	Helena	Aux Fan + Occupancy	607	16198	1383	152	18341	0.302	0.996	0.997
1st	Duluth	No IAQ fan	563	16170	1160	14	17908	0.112	4.438	4.428
1st	Duluth	Continuous IAQ fan	680	22329	1038	183	24230	0.365	0.999	0.999
1st	Duluth	Aux Fan	665	21590	1054	163	23472	0.334	0.991	0.991
1st	Duluth	Occupancy	668	21829	1037	167	23701	0.340	1.005	1.006
1st	Duluth	Aux Fan + Occupancy	655	21097	1052	147	22952	0.311	0.996	0.996
1st	Fairbanks	No IAQ fan	741	25770	886	14	27410	0.094	5.914	5.900
1st	Fairbanks	Continuous IAQ fan	922	34713	748	195	36579	0.368	0.999	0.999
1st	Fairbanks	Aux Fan	903	33792	761	175	35631	0.337	0.992	0.993
1st	Fairbanks	Occupancy	909	34014	765	180	35868	0.344	1.008	1.008
1st	Fairbanks	Aux Fan + Occupancy	889	33031	779	160	34859	0.315	0.999	0.999
1stExt	Miami	No IAQ fan	1132	21	5038	14	6204	0.090	5.050	5.039
1stExt	Miami	Continuous IAQ fan	1218	21	5741	189	7170	0.344	0.999	0.999
1stExt	Miami	Aux Fan	1213	21	5691	170	7095	0.317	0.983	0.983
1stExt	Miami	Occupancy	1183	21	5508	154	6866	0.294	1.008	1.009
1stExt	Miami	Aux Fan + Occupancy	1177	21	5455	131	6784	0.260	0.997	0.997
1stExt	Houston	No IAQ fan	871	3936	3495	14	8315	0.100	4.930	4.919
1stExt	Houston	Continuous IAQ fan	948	5058	3941	188	10136	0.354	0.999	0.999
1stExt	Houston	Aux Fan	944	4927	3918	169	9959	0.326	0.983	0.983
1stExt	Houston	Occupancy	918	5026	3761	154	9858	0.304	1.008	1.009
1stExt	Houston	Aux Fan + Occupancy	912	4802	3736	130	9580	0.269	0.996	0.997
1stExt	Phoenix	No IAQ fan	1263	2236	5257	14	8769	0.084	4.816	4.805
1stExt	Phoenix	Continuous IAQ fan	1335	3098	5524	187	10144	0.334	0.999	0.999
1stExt	Phoenix	Aux Fan	1328	2978	5502	168	9976	0.307	0.983	0.983
1stExt	Phoenix	Occupancy	1305	3090	5392	152	9940	0.285	1.007	1.008
1stExt	Phoenix	Aux Fan + Occupancy	1298	2894	5374	129	9694	0.250	0.996	0.997
1stExt	Memphis	No IAQ fan	779	5989	3318	14	10100	0.103	5.401	5.389
1stExt	Memphis	Continuous IAQ fan	860	8249	3648	192	12950	0.364	0.999	0.999
1stExt	Memphis	Aux Fan	853	7976	3632	173	12635	0.336	0.984	0.984
1stExt	Memphis	Occupancy	833	8018	3497	158	12507	0.314	1.009	1.010
1stExt	Memphis	Aux Fan + Occupancy	825	7631	3486	134	12076	0.279	0.997	0.998
1stExt	El Paso	No IAQ fan	778	3275	3557	14	7624	0.093	5.176	5.165
1stExt	El Paso	Continuous IAQ fan	828	5108	3654	190	9780	0.351	0.999	0.999

1stExt	El Paso	Aux Fan	824	4857	3659	171	9512	0.324	0.984	0.984
1stExt	El Paso	Occupancy	808	5040	3547	156	9551	0.301	1.010	1.010
1stExt	El Paso	Aux Fan + Occupancy	804	4706	3561	132	9203	0.266	0.997	0.998
1stExt	San Francisco	No IAQ fan	255	2612	1005	14	3887	0.107	4.142	4.134
1stExt	San Francisco	Continuous IAQ fan	255	4391	799	180	5625	0.351	0.999	0.999
1stExt	San Francisco	Aux Fan	254	4126	823	161	5364	0.323	0.983	0.983
1stExt	San Francisco	Occupancy	255	4167	821	145	5389	0.299	1.005	1.006
1stExt	San Francisco	Aux Fan + Occupancy	254	3857	854	121	5086	0.265	0.995	0.996
1stExt	Baltimore	No IAQ fan	651	9775	2200	14	12639	0.105	4.969	4.958
1stExt	Baltimore	Continuous IAQ fan	733	13185	2322	188	16428	0.362	0.999	0.999
1stExt	Baltimore	Aux Fan	726	12781	2327	170	16003	0.335	0.983	0.983
1stExt	Baltimore	Occupancy	708	12694	2224	154	15779	0.311	1.008	1.009
1stExt	Baltimore	Aux Fan + Occupancy	699	12175	2232	130	15237	0.276	0.996	0.997
1stExt	Albuquerque	No IAQ fan	646	7256	2423	14	10338	0.107	4.602	4.592
1stExt	Albuquerque	Continuous IAQ fan	708	10369	2400	185	13662	0.359	0.999	0.999
1stExt	Albuquerque	Aux Fan	702	9965	2414	166	13248	0.331	0.983	0.983
1stExt	Albuquerque	Occupancy	690	10134	2335	150	13309	0.308	1.007	1.007
1stExt	Albuquerque	Aux Fan + Occupancy	682	9585	2358	127	12752	0.273	0.996	0.997
1stExt	Salem	No IAQ fan	456	6564	1824	14	8858	0.117	4.518	4.509
1stExt	Salem	Continuous IAQ fan	492	9598	1640	184	11914	0.367	0.999	0.999
1stExt	Salem	Aux Fan	489	9224	1672	165	11551	0.340	0.983	0.983
1stExt	Salem	Occupancy	479	9197	1612	149	11438	0.316	1.006	1.007
1stExt	Salem	Aux Fan + Occupancy	475	8687	1657	126	10945	0.281	0.996	0.996
1stExt	Chicago	No IAQ fan	645	11243	2337	14	14240	0.106	5.176	5.165
1stExt	Chicago	Continuous IAQ fan	737	15632	2375	190	18934	0.367	0.999	0.999
1stExt	Chicago	Aux Fan	729	15163	2385	171	18448	0.339	0.984	0.984
1stExt	Chicago	Occupancy	711	14962	2282	156	18111	0.316	1.010	1.010
1stExt	Chicago	Aux Fan + Occupancy	701	14336	2302	132	17471	0.281	0.997	0.998
1stExt	Boise	No IAQ fan	574	7866	2315	14	10769	0.091	5.545	5.532
1stExt	Boise	Continuous IAQ fan	632	11569	2137	193	14531	0.356	0.999	0.999
1stExt	Boise	Aux Fan	626	11139	2162	174	14101	0.328	0.984	0.984
1stExt	Boise	Occupancy	614	11150	2094	159	14018	0.306	1.010	1.011
1stExt	Boise	Aux Fan + Occupancy	608	10575	2137	135	13455	0.270	0.998	0.998

1stExt	Burlington	No IAQ fan	583	12603	1757	14	14957	0.112	5.091	5.080
1stExt	Burlington	Continuous IAQ fan	680	17626	1701	190	20196	0.373	0.999	0.999
1stExt	Burlington	Aux Fan	670	17068	1718	171	19627	0.345	0.984	0.984
1stExt	Burlington	Occupancy	656	16805	1656	155	19272	0.321	1.008	1.009
1stExt	Burlington	Aux Fan + Occupancy	644	16081	1682	131	18538	0.287	0.997	0.997
1stExt	Helena	No IAQ fan	534	12046	1521	14	14116	0.097	4.930	4.919
1stExt	Helena	Continuous IAQ fan	624	17224	1351	188	19388	0.356	0.999	0.999
1stExt	Helena	Aux Fan	615	16652	1374	169	18811	0.328	0.983	0.983
1stExt	Helena	Occupancy	605	16507	1333	154	18598	0.305	1.008	1.009
1stExt	Helena	Aux Fan + Occupancy	593	15724	1371	130	17818	0.269	0.996	0.997
1stExt	Duluth	No IAQ fan	563	16214	1151	14	17942	0.112	4.438	4.428
1stExt	Duluth	Continuous IAQ fan	680	22379	1031	183	24273	0.365	0.999	0.999
1stExt	Duluth	Aux Fan	667	21693	1049	165	23574	0.338	0.983	0.983
1stExt	Duluth	Occupancy	654	21247	1024	148	23073	0.313	1.006	1.007
1stExt	Duluth	Aux Fan + Occupancy	637	20369	1045	125	22176	0.278	0.996	0.996
1stExt	Fairbanks	No IAQ fan	741	25839	881	14	27475	0.095	5.914	5.900
1stExt	Fairbanks	Continuous IAQ fan	923	34785	743	195	36646	0.368	0.999	0.999
1stExt	Fairbanks	Aux Fan	907	33989	758	177	35831	0.341	0.984	0.984
1stExt	Fairbanks	Occupancy	890	33299	753	162	35104	0.317	1.010	1.011
1stExt	Fairbanks	Aux Fan + Occupancy	866	32054	779	138	33836	0.281	0.998	0.999
3rd	Miami	No IAQ fan	1136	21	5053	14	6223	0.089	5.050	5.039
3rd	Miami	Continuous IAQ fan	1222	21	5759	189	7191	0.343	0.999	0.999
3rd	Miami	Aux Fan	1212	21	5687	168	7088	0.313	0.991	0.991
3rd	Miami	Occupancy	1223	21	5744	174	7162	0.321	1.005	1.006
3rd	Miami	Aux Fan + Occupancy	1212	21	5666	154	7053	0.292	0.997	0.998
3rd	Houston	No IAQ fan	874	3909	3513	14	8311	0.099	4.930	4.919
3rd	Houston	Continuous IAQ fan	952	5049	3960	188	10149	0.353	0.999	0.999
3rd	Houston	Aux Fan	944	4922	3914	167	9948	0.323	0.991	0.991
3rd	Houston	Occupancy	953	4900	3966	173	9991	0.330	1.006	1.006
3rd	Houston	Aux Fan + Occupancy	943	4793	3914	153	9804	0.301	0.997	0.997
3rd	Phoenix	No IAQ fan	1264	2229	5262	14	8769	0.083	4.816	4.805
3rd	Phoenix	Continuous IAQ fan	1336	3098	5529	187	10150	0.334	0.999	0.999
3rd	Phoenix	Aux Fan	1327	2976	5499	166	9970	0.304	0.991	0.991
3rd	Phoenix	Occupancy	1330	2998	5513	171	10012	0.311	1.006	1.006
3rd	Phoenix	Aux Fan + Occupancy	1320	2921	5472	152	9864	0.283	0.997	0.997

3rd	Memphis	No IAQ fan	782	5956	3337	14	10089	0.102	5.401	5.389
3rd	Memphis	Continuous IAQ fan	863	8230	3666	192	12951	0.363	0.999	0.999
3rd	Memphis	Aux Fan	853	7961	3631	171	12616	0.332	0.992	0.992
3rd	Memphis	Occupancy	862	7946	3688	177	12673	0.340	1.005	1.006
3rd	Memphis	Aux Fan + Occupancy	852	7726	3647	157	12383	0.311	0.998	0.998
3rd	El Paso	No IAQ fan	780	3245	3573	14	7612	0.093	5.176	5.165
3rd	El Paso	Continuous IAQ fan	830	5083	3669	190	9773	0.351	0.999	0.999
3rd	El Paso	Aux Fan	824	4852	3661	169	9506	0.320	0.991	0.991
3rd	El Paso	Occupancy	830	4853	3695	175	9553	0.328	1.005	1.006
3rd	El Paso	Aux Fan + Occupancy	824	4678	3676	155	9332	0.299	0.998	0.998
3rd	San Francisco	No IAQ fan	256	2582	1013	14	3864	0.107	4.142	4.134
3rd	San Francisco	Continuous IAQ fan	256	4355	805	180	5596	0.350	0.999	0.999
3rd	San Francisco	Aux Fan	254	4109	826	159	5349	0.320	0.990	0.990
3rd	San Francisco	Occupancy	256	4080	839	164	5338	0.326	1.005	1.005
3rd	San Francisco	Aux Fan + Occupancy	255	3898	858	144	5156	0.298	0.996	0.996
3rd	Baltimore	No IAQ fan	652	9734	2214	14	12614	0.104	4.969	4.958
3rd	Baltimore	Continuous IAQ fan	735	13154	2337	188	16414	0.361	0.999	0.999
3rd	Baltimore	Aux Fan	726	12758	2328	168	15979	0.331	0.991	0.991
3rd	Baltimore	Occupancy	731	12748	2364	173	16016	0.338	1.006	1.006
3rd	Baltimore	Aux Fan + Occupancy	721	12382	2344	153	15600	0.309	0.997	0.998
3rd	Albuquerqu e	No IAQ fan	648	7220	2436	14	10318	0.106	4.602	4.592
3rd	Albuquerqu e	Continuous IAQ fan	709	10330	2413	185	13637	0.358	0.999	0.999
3rd	Albuquerqu e	Aux Fan	702	9963	2416	164	13246	0.328	0.991	0.991
3rd	Albuquerqu e	Occupancy	707	9948	2444	169	13268	0.335	1.005	1.005
3rd	Albuquerqu e	Aux Fan + Occupancy	699	9616	2440	150	12904	0.306	0.997	0.997
3rd	Salem	No IAQ fan	458	6517	1838	14	8826	0.116	4.518	4.509
3rd	Salem	Continuous IAQ fan	493	9555	1652	184	11884	0.367	0.999	0.999
3rd	Salem	Aux Fan	488	9172	1673	164	11497	0.337	0.991	0.991
3rd	Salem	Occupancy	492	9170	1699	169	11530	0.343	1.005	1.005
3rd	Salem	Aux Fan + Occupancy	488	8838	1715	149	11190	0.314	0.997	0.997
3rd	Chicago	No IAQ fan	647	11198	2358	14	14217	0.105	5.176	5.165
3rd	Chicago	Continuous IAQ fan	738	15587	2392	190	18908	0.366	0.999	0.999
3rd	Chicago	Aux Fan	728	15104	2389	169	18390	0.336	0.991	0.991

3rd	Chicago	Occupancy	734	15111	2430	175	18450	0.343	1.005	1.006
3rd	Chicago	Aux Fan + Occupancy	723	14628	2420	155	17926	0.314	0.998	0.998
3rd	Boise	No IAQ fan	575	7843	2322	14	10755	0.091	5.545	5.532
3rd	Boise	Continuous IAQ fan	632	11537	2144	193	14506	0.355	0.999	0.999
3rd	Boise	Aux Fan	625	11086	2162	172	14045	0.324	0.992	0.992
3rd	Boise	Occupancy	628	11121	2181	178	14108	0.332	1.006	1.006
3rd	Boise	Aux Fan + Occupancy	622	10758	2193	158	13732	0.303	0.998	0.998
3rd	Burlington	No IAQ fan	584	12558	1768	14	14923	0.111	5.091	5.080
3rd	Burlington	Continuous IAQ fan	680	17580	1711	190	20160	0.372	0.999	0.999
3rd	Burlington	Aux Fan	670	17018	1720	169	19577	0.342	0.991	0.991
3rd	Burlington	Occupancy	673	17045	1742	174	19634	0.348	1.006	1.006
3rd	Burlington	Aux Fan + Occupancy	662	16510	1744	154	19071	0.320	0.998	0.998
3rd	Helena	No IAQ fan	535	12024	1528	14	14101	0.097	4.930	4.919
3rd	Helena	Continuous IAQ fan	625	17182	1358	188	19353	0.355	0.999	0.999
3rd	Helena	Aux Fan	614	16573	1376	167	18730	0.325	0.991	0.991
3rd	Helena	Occupancy	617	16637	1389	173	18815	0.332	1.006	1.006
3rd	Helena	Aux Fan + Occupancy	606	16075	1402	153	18236	0.303	0.997	0.997
3rd	Duluth	No IAQ fan	563	16168	1159	14	17904	0.112	4.438	4.428
3rd	Duluth	Continuous IAQ fan	679	22322	1037	183	24221	0.364	0.999	0.999
3rd	Duluth	Aux Fan	666	21614	1052	163	23494	0.334	0.990	0.991
3rd	Duluth	Occupancy	669	21665	1066	167	23568	0.341	1.005	1.005
3rd	Duluth	Aux Fan + Occupancy	656	20990	1076	148	22870	0.311	0.997	0.997
3rd	Fairbanks	No IAQ fan	741	25817	882	14	27454	0.094	5.914	5.900
3rd	Fairbanks	Continuous IAQ fan	922	34749	744	195	36611	0.368	0.999	0.999
3rd	Fairbanks	Aux Fan	903	33801	760	175	35639	0.337	0.992	0.992
3rd	Fairbanks	Occupancy	906	33908	760	180	35754	0.345	1.007	1.007
3rd	Fairbanks	Aux Fan + Occupancy	886	32954	772	161	34773	0.315	0.999	0.999

Table 18 Full AEQ, balanced IAQ fans. Annual data summary, organized by climate zone and occupancy pattern.

Occupancy	CZ	Auxiliary Fan Control					Occupancy Control					Auxiliary Fan + Occupancy Control					NULL Control				
		Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)
1st	Miami	8	0	58	20	85	25	0	151	18	194	32	0	205	38	274	1	0	7	16	24
1st	Houston	8	110	42	20	180	18	7	107	19	150	25	121	138	38	321	0	-76	11	16	-49
1st	Phoenix	12	95	43	20	170	13	34	62	19	128	22	125	97	38	282	-2	-30	-5	16	-22
1st	Memphis	9	236	30	20	295	15	51	96	18	181	22	284	116	38	460	-3	-202	7	15	-184
1st	El Paso	7	207	15	20	248	10	10	63	18	102	16	219	73	38	345	-2	-121	7	15	-101
1st	San Francisco	1	230	-21	20	230	3	42	9	19	72	3	256	-13	39	286	-1	-76	3	18	-56
1st	Baltimore	9	343	12	20	384	12	130	58	18	219	19	473	66	38	596	-5	-273	6	16	-257
1st	Albuquerque	8	365	1	20	394	9	56	48	19	133	16	400	43	39	497	-5	-256	3	16	-242
1st	Salem	6	359	-13	20	372	4	104	13	19	140	9	436	-4	39	479	-5	-258	5	16	-241
1st	Chicago	10	454	1	20	485	11	178	60	18	267	20	615	57	38	729	-8	-358	2	15	-349
1st	Boise	8	386	-7	20	407	4	154	4	19	180	10	533	-11	38	571	-4	-190	4	14	-175
1st	Burlington	11	526	-4	20	553	9	231	29	18	287	19	747	20	38	824	-10	-441	2	15	-433
1st	Helena	11	554	-10	20	574	8	279	8	19	313	17	810	-7	38	858	-7	-331	1	16	-321
1st	Duluth	13	645	-11	20	667	10	383	12	19	425	21	977	-1	39	1036	-12	-528	-1	17	-525
1st	Fairbanks	18	877	-11	20	905	13	663	-12	18	683	31	1504	-23	37	1548	-16	-698	0	14	-700
1stExt	Miami	5	0	46	19	71	51	0	302	41	395	56	0	354	65	475	0	0	0	17	17
1stExt	Houston	5	143	23	20	190	43	26	239	42	350	48	225	260	65	599	-2	-115	3	17	-97
1stExt	Phoenix	7	110	21	19	157	44	15	196	42	296	52	184	217	65	519	-4	-53	-10	17	-50
1stExt	Memphis	6	269	13	20	308	37	196	207	40	480	43	511	220	65	839	-5	-275	6	16	-259
1stExt	El Paso	4	235	-3	19	256	31	7	169	40	247	35	337	158	64	594	-3	-152	5	17	-133

1stExt	San Francisco	2	275	-25	19	272	3	168	-1	43	213	4	462	-31	67	502	-1	-107	7	19	-83
1stExt	Baltimore	7	388	-2	20	413	31	394	142	42	609	38	840	136	65	1079	-7	-365	6	17	-350
1stExt	Albuquerque	6	397	-12	19	410	26	196	109	42	372	31	631	89	65	817	-7	-298	2	18	-286
1stExt	Salem	3	345	-28	19	340	16	314	58	41	428	19	746	20	65	850	-7	-322	5	19	-305
1stExt	Chicago	8	466	-12	19	481	29	565	126	40	761	38	1119	110	64	1331	-10	-471	1	17	-464
1stExt	Boise	5	418	-28	20	415	21	333	75	40	469	26	862	36	64	989	-5	-264	4	15	-250
1stExt	Burlington	10	551	-15	19	565	26	695	76	41	838	36	1322	54	65	1476	-13	-596	2	17	-591
1stExt	Helena	11	617	-21	20	627	22	681	40	42	785	33	1365	9	65	1472	-11	-476	2	17	-468
1stExt	Duluth	12	680	-18	19	694	25	942	29	41	1037	40	1730	10	65	1845	-17	-713	-1	19	-712
1stExt	Fairbanks	20	965	-15	20	990	38	1622	2	41	1702	58	2679	-20	65	2782	-25	-1079	1	13	-1089
3rd	Miami	10	0	71	20	101	0	0	21	18	39	13	0	106	38	157	1	0	8	16	25
3rd	Houston	10	131	49	20	209	0	98	4	18	120	10	199	58	38	305	-1	-88	7	16	-66
3rd	Phoenix	10	109	34	20	173	7	75	23	18	123	17	136	68	38	259	-1	-26	-4	16	-15
3rd	Memphis	9	220	36	20	285	0	217	-18	18	217	10	413	31	38	492	-4	-209	6	15	-192
3rd	El Paso	6	200	14	20	239	-1	174	-23	18	168	6	330	4	38	378	-1	-112	6	15	-92
3rd	San Francisco	2	223	-18	20	227	-1	219	-34	19	203	0	389	-47	39	381	-1	-78	4	18	-57
3rd	Baltimore	10	361	16	20	406	2	326	-21	17	325	12	619	3	37	672	-6	-284	6	16	-269
3rd	Albuquerque	8	352	3	20	383	1	315	-29	19	306	9	582	-17	39	612	-5	-238	4	16	-223
3rd	Salem	5	340	-14	20	352	0	331	-42	19	309	5	589	-52	39	581	-5	-272	5	16	-256
3rd	Chicago	10	451	7	20	488	3	416	-38	18	399	13	812	-22	38	842	-8	-370	3	15	-361
3rd	Boise	6	393	-19	20	401	3	350	-33	18	338	9	684	-40	38	690	-4	-191	4	14	-177
3rd	Burlington	11	519	-4	20	546	5	447	-29	17	440	15	897	-26	38	924	-10	-456	1	15	-451
3rd	Helena	10	564	-14	20	581	6	474	-28	18	470	16	960	-38	38	975	-7	-315	2	16	-304
3rd	Duluth	13	629	-10	20	652	8	543	-27	19	543	20	1129	-33	38	1155	-12	-517	-1	17	-513
3rd	Fairbanks	19	919	-12	20	945	15	780	-16	17	797	32	1596	-25	37	1639	-16	-696	0	14	-698

Table 19 Full AEQ, unbalanced IAQ fans. Annual HVAC energy end-use savings estimates for each control type.

Occupancy	CZ	Auxiliary Fan Control					Occupancy Control					Auxiliary Fan + Occupancy Control					NULL Control				
		Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)
1st	Miami	8	0	58	20	85	33	0	208	39	280	41	0	269	59	369	1	0	7	16	24
1st	Houston	8	110	42	20	180	25	112	139	39	315	34	223	184	59	500	0	0	0	17	17
1st	Phoenix	12	95	43	20	170	25	111	109	39	284	38	213	154	59	464	1	0	8	16	25
1st	Memphis	9	236	30	20	295	23	279	118	39	459	32	517	150	59	758	0	-76	11	16	-49
1st	El Paso	7	207	15	20	248	17	188	82	39	326	24	380	99	59	563	-2	-115	3	17	-97
1st	San Francisco	1	230	-21	20	230	3	240	-12	39	271	4	467	-33	60	497	-1	-88	7	16	-66
1st	Baltimore	9	343	12	20	384	20	458	72	38	589	30	812	89	59	991	-2	-30	-5	16	-22
1st	Albuquerque	8	365	1	20	394	17	374	50	40	481	25	708	54	60	847	-4	-53	-10	17	-50
1st	Salem	6	359	-13	20	372	10	445	0	40	494	15	773	-11	60	837	-1	-26	-4	16	-15
1st	Chicago	10	454	1	20	485	21	615	63	39	738	31	1072	67	59	1228	-3	-202	7	15	-184
1st	Boise	8	386	-7	20	407	12	536	1	39	588	21	919	-3	59	997	-5	-275	6	16	-259
1st	Burlington	11	526	-4	20	553	20	747	25	39	830	30	1256	22	59	1367	-4	-209	6	15	-192
1st	Helena	11	554	-10	20	574	18	785	-1	39	840	28	1331	-13	59	1405	-2	-121	7	15	-101
1st	Duluth	13	645	-11	20	667	22	988	2	39	1051	35	1643	-8	60	1730	-3	-152	5	17	-133
1st	Fairbanks	18	877	-11	20	905	31	1487	-18	38	1539	50	2374	-27	58	2455	-1	-112	6	15	-92
1stExt	Miami	5	0	46	19	71	58	0	367	69	494	65	0	425	91	581	-1	-76	3	18	-56
1stExt	Houston	5	143	23	20	190	49	232	267	69	617	55	386	297	91	828	-1	-107	7	19	-83
1stExt	Phoenix	7	110	21	19	157	55	171	232	68	527	60	299	249	90	699	-1	-78	4	18	-57
1stExt	Memphis	6	269	13	20	308	45	581	224	68	919	52	876	241	91	1259	-5	-273	6	16	-257
1stExt	El Paso	4	235	-3	19	256	37	361	165	68	631	41	645	160	90	937	-7	-365	6	17	-350

1stExt	San Francisco	2	275	-25	19	272	4	498	-35	69	536	5	784	-64	91	816	-6	-284	6	16	-269
1stExt	Baltimore	7	388	-2	20	413	41	938	138	69	1185	48	1349	137	91	1625	-5	-256	3	16	-242
1stExt	Albuquerque	6	397	-12	19	410	33	693	93	68	887	41	1146	82	90	1359	-7	-298	2	18	-286
1stExt	Salem	3	345	-28	19	340	21	829	19	68	936	24	1225	-16	90	1323	-5	-238	4	16	-223
1stExt	Chicago	8	466	-12	19	481	41	1248	111	68	1468	50	1758	101	90	1999	-5	-258	5	16	-241
1stExt	Boise	5	418	-28	20	415	29	980	38	69	1115	35	1435	9	91	1570	-7	-322	5	19	-305
1stExt	Burlington	10	551	-15	19	565	40	1496	53	69	1658	50	2064	38	90	2242	-5	-272	5	16	-256
1stExt	Helena	11	617	-21	20	627	36	1506	9	69	1619	46	2148	-17	91	2269	-8	-358	2	15	-349
1stExt	Duluth	12	680	-18	19	694	44	1932	8	68	2051	56	2652	-15	90	2784	-10	-471	1	17	-464
1stExt	Fairbanks	20	965	-15	20	990	65	2993	-21	69	3106	84	3953	-38	92	4091	-8	-370	3	15	-361
3rd	Miami	10	0	71	20	101	10	0	95	38	143	20	0	168	59	247	-4	-190	4	14	-175
3rd	Houston	10	131	49	20	209	9	231	50	38	328	17	364	94	59	533	-5	-264	4	15	-250
3rd	Phoenix	10	109	34	20	173	14	183	51	39	287	22	311	78	59	470	-4	-191	4	14	-177
3rd	Memphis	9	220	36	20	285	9	445	17	39	509	18	667	54	59	798	-10	-441	2	15	-433
3rd	El Paso	6	200	14	20	239	5	357	-8	39	393	10	590	3	59	663	-13	-596	2	17	-591
3rd	San Francisco	2	223	-18	20	227	0	435	-52	39	422	1	644	-71	59	633	-10	-456	1	15	-451
3rd	Baltimore	10	361	16	20	406	12	666	-3	38	713	21	1017	13	59	1110	-7	-331	1	16	-321
3rd	Albuquerque	8	352	3	20	383	9	670	-28	39	690	16	1027	-27	60	1076	-11	-476	2	17	-468
3rd	Salem	5	340	-14	20	352	3	648	-67	39	623	8	977	-84	60	961	-7	-315	2	16	-304
3rd	Chicago	10	451	7	20	488	13	823	-23	39	851	23	1271	-14	59	1340	-12	-528	-1	17	-525
3rd	Boise	6	393	-19	20	401	9	744	-50	39	742	15	1153	-67	59	1160	-17	-713	-1	19	-712
3rd	Burlington	11	519	-4	20	546	15	942	-32	39	964	25	1446	-35	59	1496	-12	-517	-1	17	-513
3rd	Helena	10	564	-14	20	581	16	1030	-46	38	1038	26	1602	-64	59	1622	-16	-698	0	14	-700
3rd	Duluth	13	629	-10	20	652	21	1196	-38	39	1219	33	1830	-48	59	1875	-25	-1079	1	13	-1089
3rd	Fairbanks	19	919	-12	20	945	33	1664	-29	38	1706	51	2561	-43	58	2627	-16	-696	0	14	-698

Table 20 Half AEQ, unbalanced IAQ fans. Annual HVAC energy end-use savings estimates for each control type.

Occupancy	CZ	Auxiliary Fan Control					Occupancy Control					Auxiliary Fan + Occupancy Control					NULL Control				
		Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)	Air Handler (kWh/yr)	Furnace (kWh/yr)	Compressor (kWh/yr)	Mech Vent (kWh/yr)	Total (kWh/yr)
1st	Miami	8	0	61	21	90	18	0	124	16	158	25	0	176	36	236	1	0	7	16	24
1st	Houston	8	141	40	21	210	15	37	89	17	157	21	175	118	36	349	0	0	0	17	17
1st	Phoenix	11	97	40	21	168	8	27	39	17	90	17	134	71	36	258	1	0	8	16	25
1st	Memphis	10	293	30	21	354	12	110	71	16	209	19	373	91	35	519	0	-76	11	16	-49
1st	El Paso	7	255	12	21	295	6	56	35	16	113	11	279	40	36	367	-2	-115	3	17	-97
1st	San Francisco	1	260	-24	20	257	1	62	-4	17	75	2	320	-29	36	328	-1	-88	7	16	-66
1st	Baltimore	10	418	9	21	457	11	250	44	17	322	19	615	46	36	715	-2	-30	-5	16	-22
1st	Albuquerque	8	383	-4	21	408	6	99	26	17	147	14	485	20	36	554	-4	-53	-10	17	-50
1st	Salem	5	394	-20	21	400	4	169	1	16	191	9	571	-23	36	593	-1	-26	-4	16	-15
1st	Chicago	10	490	-2	21	519	11	256	45	16	327	20	759	38	36	853	-3	-202	7	15	-184
1st	Boise	9	460	-11	21	478	3	175	-4	16	190	10	623	-26	35	642	-5	-275	6	16	-259
1st	Burlington	11	571	-10	21	592	9	355	15	16	396	20	935	3	36	993	-4	-209	6	15	-192
1st	Helena	11	600	-16	21	615	7	329	0	17	353	19	954	-19	36	990	-2	-121	7	15	-101
1st	Duluth	14	739	-15	21	758	11	500	1	16	528	25	1231	-14	36	1278	-3	-152	5	17	-133
1st	Fairbanks	19	922	-13	21	948	13	699	-17	16	711	33	1682	-31	35	1720	-1	-112	6	15	-92
1stExt	Miami	6	0	50	19	75	36	0	233	35	304	41	0	286	58	386	-1	-76	3	18	-56
1stExt	Houston	4	131	23	19	177	30	33	180	35	278	37	257	205	58	556	-1	-107	7	19	-83
1stExt	Phoenix	7	120	22	19	168	29	8	132	35	204	37	204	150	58	450	-1	-78	4	18	-57
1stExt	Memphis	7	273	16	19	315	27	230	152	34	443	35	618	163	58	874	-5	-273	6	16	-257
1stExt	El Paso	4	251	-6	19	268	20	68	107	35	229	24	402	93	58	577	-7	-365	6	17	-350
1stExt	San Francisco	1	265	-24	19	261	1	223	-22	35	237	1	534	-55	58	539	-6	-284	6	16	-269

1stExt	Baltimore	7	404	-5	19	424	25	491	98	35	649	33	1010	90	58	1191	-5	-256	3	16	-242
1stExt	Albuquerque	6	403	-14	19	414	18	235	65	35	353	25	784	42	58	910	-7	-298	2	18	-286
1stExt	Salem	3	374	-32	19	364	13	401	28	35	476	17	911	-17	58	969	-5	-238	4	16	-223
1stExt	Chicago	8	469	-10	19	486	26	671	92	35	823	36	1296	73	58	1463	-5	-258	5	16	-241
1stExt	Boise	6	431	-25	19	430	17	419	43	34	514	23	994	1	58	1076	-7	-322	5	19	-305
1stExt	Burlington	9	558	-17	19	569	24	820	44	35	924	35	1545	19	58	1657	-5	-272	5	16	-256
1stExt	Helena	9	572	-23	19	577	20	717	19	35	790	31	1500	-19	58	1570	-8	-358	2	15	-349
1stExt	Duluth	12	686	-19	19	698	26	1132	7	35	1199	42	2010	-14	58	2096	-10	-471	1	17	-464
1stExt	Fairbanks	16	796	-15	19	815	33	1486	-10	34	1543	57	2731	-36	58	2810	-8	-370	3	15	-361
3rd	Miami	10	0	73	21	103	-1	0	15	16	29	10	0	93	35	138	-4	-190	4	14	-175
3rd	Houston	8	127	45	21	201	-1	150	-7	16	158	8	256	45	35	345	-5	-264	4	15	-250
3rd	Phoenix	8	122	30	21	181	6	100	16	16	138	16	177	58	35	286	-4	-191	4	14	-177
3rd	Memphis	10	269	36	21	335	1	283	-22	15	278	10	503	19	35	568	-10	-441	2	15	-433
3rd	El Paso	5	231	9	21	266	0	230	-26	15	219	6	406	-7	35	440	-13	-596	2	17	-591
3rd	San Francisco	2	246	-21	20	247	0	275	-34	16	258	0	457	-53	36	440	-10	-456	1	15	-451
3rd	Baltimore	9	396	9	21	435	3	406	-26	16	398	14	772	-7	35	814	-7	-331	1	16	-321
3rd	Albuquerque	7	367	-4	21	391	2	382	-32	16	368	10	714	-27	35	732	-11	-476	2	17	-468
3rd	Salem	5	383	-21	21	387	1	385	-47	15	354	6	717	-63	35	695	-7	-315	2	16	-304
3rd	Chicago	10	483	4	21	518	4	476	-38	15	458	16	959	-28	35	982	-12	-528	-1	17	-525
3rd	Boise	7	451	-18	21	461	4	416	-37	15	398	10	779	-49	35	774	-17	-713	-1	19	-712
3rd	Burlington	10	562	-10	21	583	7	534	-31	16	526	18	1069	-33	35	1089	-12	-517	-1	17	-513
3rd	Helena	11	609	-18	21	623	7	545	-31	16	538	18	1107	-44	35	1117	-16	-698	0	14	-700
3rd	Duluth	13	708	-15	21	727	10	656	-29	16	653	24	1332	-39	35	1351	-25	-1079	1	13	-1089
3rd	Fairbanks	19	947	-16	21	972	17	841	-16	15	856	36	1794	-28	35	1837	-16	-696	0	14	-698

Table 21 Full AEQ, balanced IAQ fans. Annual HVAC energy end-use savings estimates for each control type.