APPENDIX B: Title 24 Fan Sizing and Airtightness Requirements for New California Homes

Abstract

Since 2008, California has had building code (also known as Title 24) requirements for minimum ventilation. This simulation study is a companion to a field study of new California homes to determine if the ventilation requirements are resulting in acceptable indoor air quality (IAQ). The simulation study aims to look beyond current home performance to examine potential future changes to the California Code. The main objectives of this simulation study were to: (1) evaluate the IAQ and energy impacts of different whole house (or dwelling unit) fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH50 airtightness requirement in the Title 24 energy code. Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of the Title 24 Building Energy Code, across a number of California climate zones (CZ 1, 3, 10, 12, 13 and 16) reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH50, and whole house fans were sized according to six currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type, or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The simulations used the relative exposure approach to assess IAQ where the exposure to a generic continuously emitted indoor contaminant is compared to the exposure using a known fixed air flow – in this case the whole house target airflow (Q_{total}) required by ASHRAE Standard 62.2. The results for individual cases were combined using a weighting based on the fraction of new homes constructed in different climate zones to get statewide estimates of performance.

The whole house ventilation fan sizing methods with the poorest weighted average IAQ (highest relative exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24 2008) and the Total Ventilation Rate Method (T24 2013). These had weighted average relative exposures of 1.3 and 1.4, respectively. Of all sizing methods, the adopted ***Title 24 2019*** sizing method with a sub-additivity adjustment for unbalanced fans maintained relative exposure closest to 1.0. The ASHRAE 62.2-2016 method and the ***Qtotal*** method were the next best approaches. The ASHRAE 62.2-2016 fan/infiltration superposition method consistently under-ventilated and had relative exposures in the range of 1.05 to 1.09, while the ***Qtotal*** method consistently over-ventilated, with relative exposures of about 0.93 to 0.97. ***Qtotal*** was the only sizing method that maintained exposure below 1.0 in all simulated cases. The best approaches from an IAQ standpoint were the T24 ***2019*** and ***Qtotal*** methods. They increased the weighted average energy use by 3 and 5% relative to the ASHRAE 62.2-2016 method. The difference in weighted average total energy consumption between any of these three sizing methods was roughly 350 kWh/year.

Most of the sizing methods had widely spread relative exposure values, meaning that most homes were either substantially under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either poor IAQ or excess energy consumption for individual homes, even when the weighted average results are acceptable. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type, had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the CEC could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The 2019 Title 24 fan sizing method resulted in exposure values nearly as tightly clustered as the ASHRAE 62.2-2016 method, though it consistently over-ventilated leaky homes relative to the target airflows in the standard and energy code, with increased site energy consumption ranging from 70 to, 1,400 kWh/year, when averaged across climate zones.

An airtightness requirement of 3 ACH50 in new California homes was found to have predicted weighted average energy savings of about 1 to 5% of total HVAC energy use. Most of these savings were from reducing the ventilation rate and worsening IAQ. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5%) but worsened IAQ (increasing exposure to a generic indoor contaminant by 5 to 24%). The energy savings are low because the majority of new home construction is in mild climates, and the interactions between unbalanced mechanical ventilation and natural infiltration lead to small changes in total airflow when we tighten to this limit. Energy use decreased as weighted average exposure increased, essentially trading off poor IAQ for improved energy performance. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1%) under an airtightness requirement, while they marginally improved IAQ (reduced exposure by roughly 3 to 4%). Airtightness savings were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates due to having greater natural infiltration airflows. Savings were also higher in climates with the harshest weather (CZ16 and CZ1), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. When HVAC energy use was normalized such that pollutant exposure was the same in all cases, the energy savings attributable to a 3 ACH50 airtightness limit dropped to well below 1%.

The determination of which fan sizing method is most appropriate for new homes in California will largely depend on whether or not the state decides to impose an airtightness requirement in the building energy code (and require HERS raters to measure it). Our results suggest that unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening. On average, the adopted 2019 fan sizing method for Title 24 performed similarly to the more complicated ASHRAE 62.2-2016 method under current airtightness conditions. The adopted fan sizing method gave weighted average exposure very near to 1.0 under both current and hypothetical airtightened scenarios, though exposure would increase roughly 5% under a hypothetical airtightness requirement in the energy code.

1 Introduction

The provision of air exchange in residences to dilute indoor pollutants was traditionally provided by weather-induced natural infiltration and operation of windows and doors, as seen fit by the occupants (Janssen, 1999; Sundell, 2004). Most homes were exceptionally leaky and maintained much more air exchange throughout the year than was required to maintain acceptable indoor conditions, which wasted large amounts of energy. As builders and consumers became conscious of the energy consumed by homes in the late 1970s, air sealing of the building envelope became a very early 'low-hanging fruit' target of energy efficiency efforts. Aggressive airtightening and insulating efforts were initially performed without adding any intentional ventilation to the homes, and reports of mold, moisture and poor IAQ were promulgated throughout the building community (Less, Mullen, Singer, & Walker, 2015).

Many building energy professionals realized that mechanical ventilation was required in airtightened homes in order to maintain air quality that was acceptable to occupants. Mechanical ventilation mandates slowly spread across the world, with strong government requirements for new homes in Canada (Gusdorf & Hamlin, 1995; Gusdorf & Parekh, 2000; Riley, 1987) and internationally, and in the U.S. certain energy efficiency programs and jurisdictions incorporated ventilation into regional construction practice and codes (Mudarri, 2010). Currently, the need for mechanical ventilation in new homes is recognized in model codes, by many local jurisdictions and by programs such as the US DOE weatherization.

The ventilation standard in the United States—ASHRAE Standard 62.2 (ANSI/ASHRAE, 2016)—currently specifies a target whole house ventilation rate that varies by floor area and occupancy, and is closely aligned with the rule of thumb air exchange target that energy and air quality professionals have long touted as the ideal energy-IAQ compromise—roughly 0.3 to 0.35 air changes per hour (hr^{-1}).

California's Building Energy Efficiency Standards (Title 24) has recognized the need for builders to install continuous mechanical ventilation in new homes (and some remodeled homes) since 2008. The 2008 updates to Title 24 included a mandatory requirement that new residences and additions >1,000 ft^2 provide mechanical ventilation meeting the requirements of the ASHRAE Standard 62.2-2007. Reliance on operable windows for compliance was explicitly prohibited. This change in IAQ ventilation requirements was spurred by an IAQ field study in new California homes that showed low ventilation rates in new (at the time) California homes with moderately high formaldehyde concentrations (Offermann, 2009). A companion survey study also demonstrated that a substantial minority of new California homes had windows closed continuously during heating and cooling seasons (Price, Sherman, Lee, & Piazza, 2007). Together, these studies were used to support mandatory inclusion of mechanical ventilation in new California homes for IAQ.

Airtightness in new homes has also increased with improved construction methods and technologies, and the International Energy Conservation Code (IECC) now recognizes a 3 ACH_{50} airtightness target for U.S. DOE Climate Zone 3 and above (5 ACH_{50} in zones 1 and 2), which includes most of California (ICC, 2012). The Title 24 requirements and paths to compliance, as well as the mandates of the ASHRAE Standard 62.2, have also continued to evolve over the past decade. As such, there are currently a number of different ways to comply with the IAQ provisions of Title 24. None of these compliance paths align perfectly with the current requirements in the ASHRAE 62.2-2016 ventilation standard. As in the past, we anticipate that the California Energy Commission may adopt the current 62.2 standard in part, with California-specific provisions or adjustments. Builder practice around Whole house fan sizing and installation in California (Chan et al. 2018 and Stratton et al 2012a) is to install systems with considerable excess capacity (by 40-50%), which does not align with any of the specified options. This indicates that builders are not deliberately designing systems to operate at minimum airflows required by code. For this reason we will include this current builder practice as a fan sizing option in this study.

This simulation study is being performed in parallel with a field study of pollutant concentrations in new California homes built to the 2008 Title 24 building energy code (Chan et al. 2018). The main goals of this simulation effort are to quantify the energy, ventilation and IAQ impacts of airtight residences under current and proposed IAQ compliance paths available in the Title 24 building energy code and the ASHRAE 62.2 ventilation standard. Specifically, we will examine how different levels of envelope airtightness and methods of sizing Whole house fans affect exposure to pollutants and HVAC energy use. This will to provide information that will help to guide the California Energy Commission's decision whether or not to include an airtightness requirement in the Title 24 Building Energy Code, as well as an IAQ ventilation specification that compliments this requirement without causing harm.

The two primary objectives are:

- Assess the energy and IAQ impacts of different fan sizing methods currently available or proposed for California Title 24 compliance in new homes.
- Determine the impacts of a proposed 3 ACH50 airtightness requirement under the various fan sizing methods.

2 Background

2.1 IAQ and Relative Exposure

In this work, IAQ impacts are assessed using the metric of relative exposure. This metric was first proposed as an approach for assessing intermittent ventilation, based on equivalent dose and exposure to a generic, continuously emitted indoor contaminant. Equivalence was assessed relative to a fixed airflow ventilation system (Sherman, Mortensen, & Walker, 2011; Sherman, Walker, & Logue, 2012). The metric of relative exposure is now the accepted method of determining compliance for time-varying ventilation approaches in the ASHRAE 62.2-2016 standard.

The relative exposure reflects the real-time ratio between the concentrations of a generic, continuously emitted, indoor contaminant, under two different ventilation rates. First, is a fixed ventilation rate that represents the target airflow for the home (in this study we used ASHRAE 62.2-2016), and second is the time-varying airflow actually experienced by the house.

At a given time step, a relative exposure equal to 1 means the two ventilation rates lead to identical pollutant concentrations. When averaged over a period of time (e.g., annually), a value of 1 means the two rates provide equivalent pollutant exposure. 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 requirements.

The relative exposure can be interpreted as a multiplier that could be applied to any generic contaminant emitted uniformly and continuously from only indoor sources. For example, a value of 1.2 reflects a 20% increase in pollutant concentration, relative to the concentration if the home's ventilation (Q_i) was at the target ventilation rate (Q_{total}). Or a value of 0.66 would reflect a 34% reduction in the pollutant concentration, relative to the concentration at the target ventilation rate.

In general, the pollutant concentration is inversely related to the ventilation rate. As a result, the increased airflow required to reduce the concentration is much greater than the reduction in airflow needed to result in a similar increase in the concentration. For example, a home at 0.5 ACH hr^{-1} and a formaldehyde concentration of 30 ppb would need to double its airflow to 1 ACH hr^{-1} in order to halve the concentration to 15 ppb. But the house would reach 45 ppb (30 + 15) after only a 33% reduction in the ventilation rate, from 0.5 to 0.23 ACH hr^{-1}. The end result of this is that it requires more airflow more to reduce a pollutant concentration than is saved by allowing the concentration to increase.

2.2 Airtightness, IAQ and Energy Consumption

Overall, reducing air leakage while mechanically ventilating to maintain equivalent IAQ is expected to save energy for two reasons: (1) it reduces the variability in the ventilation rate throughout the year, shifting airflows to milder weather conditions, and (2) this reduction in variability means the same exposure can be maintained with a lower total airflow. Both of these effects reduce the heating and cooling loads associated with ventilation, even when the same relative exposure is maintained.

A principle of equivalent ventilation is that as the airflow gets more variable, a higher average flow is required to maintain equivalent exposure. For this reason, in addition to shifting ventilation to milder periods, the airtight, mechanically vented home requires a lower annual average ventilation rate to achieve the same exposure as a leaky home. The most airtight cases effectively have a fixed house airflow that is equal to the fan airflow. Their flows do not increase or decrease with outside conditions. In contrast, a leaky home has widely varying ventilation rates determined by weather conditions, and it will require substantially higher total annual airflow to achieve relative exposure equal to that of the airtight home.

3 Method

The REGCAP simulation tool is used to predict the ventilation and energy performance. It combines detailed models for mass-balance 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. REGCAP is implemented using a one-minute time-step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance.

3.1 Prototype Descriptions

Two CEC prototype homes were simulated—one- and two-story, referred to throughout as "med" (or "medium") and "large", respectively (Nittler & Wilcox, 2006). These were made to align as well as possible with the prescriptive performance requirements (Option B) in the 2016 Title 24 energy code. Thermostat schedules were set to meet those specified in the 2016 ACM (see Table 1). HVAC equipment was sized using ACCA Manual J load calculation procedures. Current deviations from the Title 24 prescriptive path prototypes include no whole house economizer fans, internal gains based on RESNET calculation method, HVAC equipment efficiencies and elimination of duct leakage to outside. Equipment efficiency was increased beyond prescriptive minimums to SEER 16 A/C and 92 AFUE gas furnaces in order to align with standard new construction practice encountered in the parallel field study of new California homes (Chan et al. 2018) and based on input from the project's Technical Advisory Committee.

Table 2 summarizes the prototype home parameters that were exercised in this study. The climate zones were chosen to capture a range of heating and cooling loads. The airtightness ranged from current practice of 5 ACH_{50} down to passive house levels of 0.6 ACH_{50}. This included an airtightness of 3 ACH_{50} that could be adopted as a maximum level for the state to align with the requirements of the International Energy Conservation Code that is increasingly being used elsewhere in the country. The ventilation fan for Title 24 compliance was sized according to seven different calculation methods, which are discussed in detail in Section 3.4. Each case was simulated with both balanced and unbalanced Whole house fans. A baseline case with no Whole house fan operating was simulated for each combination of prototype, airtightness and climate zone. The ventilation energy use was the difference in total annual HVAC consumption between the fan and no fan cases, which includes changes in fan energy and thermal loads from air exchange.

Table 1 HVAC thermostat schedule per Title 24 ACM Table 19

Hour of Day	Heating Set-Point (°F)	Cooling Set-Point (°F)
0:00	65	78
1:00	65	78
2:00	65	78
3:00	65	78
4:00	65	78
5:00	65	78
6:00	65	78
7:00	68	83
8:00	68	83
9:00	68	83
10:00	68	83
11:00	68	83
12:00	68	83
13:00	68	82
14:00	68	81
15:00	68	80
16:00	68	79
17:00	68	78
18:00	68	78
19:00	68	78
20:00	68	78
21:00	68	78
22:00	68	78
23:00	65	78

Table 2 Summary of the parameters that were varied in HENGH simulations.

<table>
<tr><th>Prototype Home</th><th colspan="120">1-story, 2,100 ft²</th><th colspan="120">2-story, 2,700 ft²</th></tr>
<tr><td>CEC Climate Zone</td><td colspan="40">1 (Arcata)</td><td colspan="40">3 (Oakland)</td><td colspan="40">10 (Riverside)</td><td colspan="40">12 (Sacramento)</td><td colspan="40">13 (Fresno)</td><td colspan="40">16 (Blue Canyon)</td></tr>
<tr><td>Envelope Airtightness (ACH_{50})</td><td colspan="48">0.6</td><td colspan="48">1</td><td colspan="48">2</td><td colspan="48">3</td><td colspan="48">5</td></tr>
<tr><td>Whole house fan Sizing Method</td><td colspan="30">None</td><td colspan="30">T24_2008</td><td colspan="30">T24_2013</td><td colspan="30">Qtotal</td><td colspan="30">ASHRAE 62.2-2016</td><td colspan="60">T24_2019</td><td colspan="30">Builder Practice</td></tr>
<tr><td>Fan Type</td><td colspan="120">Exhaust</td><td colspan="120">Balanced</td></tr>
</table>

3.2 Weighted Average Calculations

To scale these individual cases up to statewide estimates, we developed weighting factors that represent our best estimate of the current distribution of parameters. A second series of weighting factors were developed to represent a proposed envelope leakage requirement of 3 ACH_{50}.

Each case is weighted according to the expected distribution of the parameter in new homes throughout the state. The weighted average parameters used in our analysis included climate zone (see Table 7), envelope airtightness (Table 3), house prototype (Table 4) and fan type (Table 5). Each factor is briefly discussed below. This is an imperfect approach to characterizing the entire new California single-family building stock, but it does give us a way to generalize and summarize our results. For example, this method gives greater weight to results from the mild climate zones in Southern and Central California where most new home development occurs in the state, and it reduces the effect of the larger energy impacts in sparsely populated zones, like CZ1 (Arcata) or 16 (Blue Canyon). The average result under these weights for each fan sizing method was calculated using Equation 1.

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

x = Variable in question (e.g., relative exposure, ventilation energy use)

$w_{prototype}$ = house prototype weight

w_{cz} = climate zone weight

w_{ACH50} = airtightness weight

$w_{fantype}$ = fan type weight

The airtightness weights used to estimate the impacts of an air leakage requirement in new California homes are shown in Table 3. The airtightness weights are designed to roughly estimate the airtightness distribution in new California homes, with most new construction achieving roughly 5 ACH_{50}, and diminishing numbers of new homes achieving 3 ACH_{50} and very low numbers with greater airtightness. The weighting factors are based on the results of the following field studies. Proctor, Chitwood, & Wilcox (2011) reported median envelope leakage in 38 new CA homes of 4.66 ACH_{50}. They found that only 7.8% of homes were below 3 ACH_{50}. The HENGH field study (Chan et al. (2018)) in new California homes has found very similar airtightness results, with a median of 4.5 ACH_{50}; 6% of HENGH homes were below 3 ACH_{50}, 26% were between 3 and 4 ACH_{50}, and 68% exceeded 4 ACH_{50}. Consistent with these field studies, we placed 93% of airtightness weight in the 3 and 5 ACH_{50} homes, and 7% of airtightness weight in the 2 ACH_{50} or less categories. The weights under the proposed 3 ACH_{50} airtightness requirement (Table 3, Row 2) simply shift these down (e.g., from 5 to 3, 3 to 2, etc.), such that nearly all new homes achieve either 3 or 2 ACH_{50}, with very small numbers that are more airtight or non-compliant with the limit. We do not have real-world estimates of what happens to home airtightness under a code-imposed air leakage limit, but we estimate that a small fraction of homes will miss the target, and all others will be fairly tightly clustered below the code requirement.

Table 3 Envelope airtightness weighting factors

Envelope airtightness weighting factors	**Envelope Airtightness (ACH_{50})**				
	5	3	2	1	0.6
Current	0.63	0.30	0.05	0.01	0.01
Proposed 3 ACH_{50}	0.01	0.63	0.30	0.05	0.01

Prototype weights (Table 4) match those provided in the description of the single-family Title 24 prototype buildings that are used for analysis supporting development of Title 24 (Nittler & Wilcox, 2006). Fan type weights (Table 5) prioritize exhaust fans, with a modest 10% of new homes having balanced ventilation systems. This is consistent with findings from the companion field study to this simulation effort (Chan et al. (2018)), where 64 of 70 homes used an exhaust fan to comply with Title 24 ventilation requirements. This aligns with prior assessments of ventilation in new California homes, which found that the vast majority of new homes use unbalanced exhaust ventilation systems to comply with Title 24 (Stratton, Walker, & Wray, 2012a).

Table 4 Prototype weighting factors

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

Table 5 Fan type weighting factors.

Fan Type	Exhaust	Balanced
Weight Factor	0.90	0.10

Climate zone weights (Table 6 and Table 7) are based on the fraction of total projected new housing starts in 2017 in each CEC climate zone, using data provided to the 2016 CASE teams by the CEC Demand Analysis office. We have reproduced exactly the estimates provided by Rasin & Farahmand (2015) in Table 14 of the Residential High Performance Walls CASE report. Yet, we simulated only climate zones 1, 3, 10, 12, 13 and 16, and we attribute projected housing starts in non-simulated climate zones based on geography and overall heating/cooling degree days (see Table 6 for our assignment of non-simulated climates to those we simulated, for example, the CZ4 and CZ5 weights were added to the CZ12 weight). The combined weights for zones 1, 3, 10, 12, 13 and 16 are provided in Table 7.

Table 6 New construction estimates for single-family homes in 2017 and weighting assignments for un-simulated climate zones.

CZ	City	2017 New Single-Family Homes	2017 New Homes Fraction	Rough HDD_{65} Range	Rough CDD_{80} Range	CZ Weight Assignment
1	Arcata	695	0.006	3800-4500	0-50	1
2	Santa Rosa	2602	0.024	2600-4200	200-900	3
3	Oakland	5217	0.048	2500-3800	10-500	3
4	San Jose-Reid	5992	0.055	2300-2900	200-1000	12
5	Santa Maria	1164	0.011	2300-3000	200-900	12
6	Torrance	4142	0.038	700-1900	500-1200	10
7	San Diego-Lindbergh	6527	0.060	1300-2000	500-1100	10
8	Fullerton	7110	0.066	1300-1800	700-1300	10
9	Burbank-Glendale	8259	0.076	1100-1700	1300-1600	10
10	Riverside	16620	0.154	1600-1900	1400-1900	10
11	Red Bluff	5970	0.055	2500-4300	600-1900	3
12	Sacramento	19465	0.180	2400-2800	900-1600	12
13	Fresno	13912	0.129	2000-2700	1000-2200	13
14	Palmdale	3338	0.031	1900-2700	2000-4200	13
15	Palm Spring-Intl	3885	0.036	1000-1300	4000-6600	10
16	Blue Canyon	3135	0.029	4300-6000	200-1000	16

Table 7 Climate zone weighting factors.

	1 (Arcata)	3 (Oakland)	10 (Riverside)	12 (Sacramento)	13 (Fresno)	16 (Blue Canyon)
Total Weight Factor	0.006	0.128	0.431	0.246	0.160	0.029

3.3 Energy Use Normalization with Relative Exposure

Most of the results presented in this work are raw simulation outputs in which the IAQ provided in each case is not the same. When assessing energy savings from an airtightness requirement, this means the results presented in Section 4.1 conflate changes in airtightness with changes in the ventilation rate and relative exposure. To isolate the energy associated with ventilation from other envelope loads, we simulated cases with no fan operation and no envelope leakage. The energy use for these envelope-only cases was subtracted from the total to get the ventilation-only component. We used these ventilation-only energy use estimates to determine estimates of energy savings normalized by relative exposure. This is achieved by simply multiplying the ventilation-only energy estimates by the relative exposure in this case. E.g., a relative exposure of 1.2 would lead to a 20% increase in energy use to correct to a relative exposure of 1. While this assumed linear response my not be exactly true in all cases it is the only way to achieve comparisons at the same relative exposure without considerable manual iteration. The total HVAC energy use was then calculated for each case by adding the adjusted ventilation energy use back onto the envelope-only HVAC energy use to provide an estimate of energy use for each case when they are forced to provide the same exposure. These exposure-adjusted adjusted total energy use values are presented separately in Section 4.2.

3.4 Whole House Mechanical Ventilation in Title 24

Since the 2008 code cycle, California's Title 24 building energy code has required whole house mechanical ventilation in new homes and in additions >1,000 ft^2. The code requirements have evolved to include multiple calculation methods for sizing the fans. In this study, we examined six fan sizing methods available to designers and to the Energy Commission in specifying requirements of the 2019 Title 24. There are sizing methods that explicitly account for natural infiltration and those that do not (described in detail in Section 3.4.1 and 3.4.2). The fan sizing methods are summarized in Table 9. All calculated fan sizes are illustrated for each sizing method in Appendix B-1 (Figure 28 through Figure 33).

3.4.1 Whole house fan Size Calculation Without Natural Infiltration

We assessed three fan sizing methods that include no direct estimates of natural infiltration, and their calculated fan airflows do not vary by the factors that affect infiltration, namely airtightness, house geometry and climate zone.

3.4.1.1 Fan Ventilation Rate Method (T24_2008)

The Fan Ventilation Rate method (referred to as ***T24_2008***) was added as a requirement in the Title 24 (2008) Residential Compliance Manual Section 4.6.2. It calculates Whole house fan airflow from conditioned floor area and occupancy, as shown in Equation 2. This was the fan sizing equation in the version of ASHRAE 62.2 at the time the requirement was written. This fan sizing approach implicitly assumed a background infiltration rate equivalent to 0.02 cfm per ft^2 of conditioned floor area. This is an appropriate natural infiltration rate assumption for homes in the 5-7 ACH_{50} range, but it is inadequate for substantially airtight homes. The T24_2008 method results in fan sizes that do not vary by either airtightness or location. This fan sizing method continues to be available in the current 2016 Title 24, and it is the default sizing method for IAQ ventilation in the prescriptive and performance path homes.

$$Q_{fan} = \frac{A_{floor}}{100} + 7.5 \times (N_{br} + 1) \qquad \textbf{(2)}$$

Q_{fan} = calculated Whole house fan airflow, cfm

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

N_{br} = number of bedrooms

3.4.1.2 Current Builder Practice Method (BuilderPractice)

Field research suggests that current builder practice in California homes results is to install a Whole house fan that is oversized relative to the T24_2008 airflow requirement by roughly 40%[1]. We refer to this fan sizing as ***BuilderPractice*** and use a 40% oversized fan in the simulations (calculated using Equation 3). We hypothesize that this over-sizing is the result of builders rounding up the required airflow rates to match that of the nearest retail fan.

$$Q_{fan} = 1.4 \times Q_{fan,T24\_2008} \qquad \textbf{(3)}$$

[1] The 70 homes studied in the companion field study (Chan e al. (2018)) had an average measured fan flow 50% above the minimum requirement. However all these data were not available at the time of performing the simulations and a 40% value was used based on the initial field study results and the results of Stratton et al. (2012) in 15 California homes.

3.4.1.3 Total Ventilation Rate Method (Qtotal)

In 2013, an alternative IAQ compliance path for airtight, low-infiltration homes was added to Title 24 named the Total Ventilation Rate method. Homes using the Total Ventilation Rate method would typically calculate a fan size by subtracting an infiltration estimate from a whole house target airflow. This is based directly on changes to ASHRAE 62.2 that explicitly changed the basic equations to from fan sizing (based on an assumed natural infiltration air flow of 2 cfm/100 sq. ft. of floor area) to a total ventilation target. In this no-infiltration sizing method (referred to as ***Qtotal***), we simply set the Whole house fan airflow equal to the whole house ventilation airflow target, as in Equation 4, where the fan airflow is equal to Q_{tot}.

$$\mathbf{Q_{tot} = 0.03\ A_{floor} + 7.5 \times (N_{br} + 1)} \quad \textbf{(4)}$$

3.4.2 Whole house fan Size Calculation With Natural Infiltration

Four Whole house fan sizing methods are examined that include natural infiltration estimates with varying levels of sophistication, all of which are based on the methods in the ASHRAE 62.2 ventilation standard. ASHRAE 62.2-2016 is structured to help ensure that all compliant homes have similar whole house airflows that are consistent with the target airflow set by the standard (Q_{tot}). We begin by outlining the general process of calculating a whole house target airflow (Q_{total}), an infiltration estimate (Q_{inf}) and a resulting Whole house fan airflow (Q_{fan}). We then highlight where specific fan sizing methods diverge from this general approach.

3.4.2.1 Total Ventilation Rate Method Including Infiltration (T24_2013)

Here we take the Total Ventilation Rate method and account for natural infiltration in the Whole house fan sizing (referred to as ***T24_2013***).

A target ventilation airflow (Q_{total}) for the combined natural and mechanical flows is calculated using Equation 4. The natural infiltration airflow (Q_{inf}) is estimated from blower door air leakage, house geometry and climate data. The normalized leakage is calculated using the effective leakage area from a blower door measurement, combined with the conditioned floor area and height of the building using Equation 5. The annual effective natural ventilation airflow (Q_{inf}) is calculated using Equation 6 using the weather and shelter factor (*wsf*). The *wsf* is designed to give an annual average infiltration airflow estimate that would provide pollutant exposure equivalent to that under time-varying infiltration airflows and includes on assumptions about wind shelter and envelope leakage distribution. A *wsf* value for each TMY3 climate file location is provided in Normative Appendix B-1 to ASHRAE 62.2-2016. The weather file locations and *wsf* values used in the HENGH simulations are reproduced in Table 8. Turner et al. (2012) describe the methods used to calculate the *wsf* factors for the 62.2 standard.

The fan airflow (Q_{fan}) is calculated as the difference between the target ventilation rate and the natural infiltration rate using Equation 7.

$$\mathbf{NL = 1000 \times \left[\frac{ELA}{A_{cond}}\right] \times \left[\frac{H}{H_{ref}}\right]^{Z}} \quad \textbf{(5)}$$

NL = normalized leakage
ELA = effective leakage area, ft^2
H = vertical distance between the lowest and highest above-grade points within the pressure boundary, ft
H_{ref} = reference height for one-level of home, 8.2 ft

$$\mathbf{Q_{inf} = \frac{NL \times wsf \times A_{floor}}{7.3}} \quad \textbf{(6)}$$

Q_{inf} = Effective annual infiltration rate, cfm
NL = normalized leakage
wsf = weather and shielding factor from Normative Appendix B-1 62.2-2016
A_{floor} = floor area of residence, ft^2

$$\mathbf{Q_{fan} = Q_{total} - Q_{inf}} \quad \textbf{(7)}$$

Q_{fan} = required mechanical ventilation rate, cfm
Q_{total} = Total required ventilation rate, cfm
Q_{inf} = Effective annual infiltration rate, cfm

Table 8 CEC climate zones, representative cities, selected TMY3 id and site locations, and weather and shielding factors (wsf) for fan sizing in HENGH simulations.

CZ	Representative City	TMY3 ID	TMY3 Site Name	wsf
1	Arcata	725945	ARCATA AIRPORT	0.56
2	Santa Rosa	724957	SANTA ROSA (AWOS)	0.49
3	Oakland	724930	OAKLAND METROPOLITAN ARPT	0.54
4	San Jose-Reid	724945	SAN JOSE INTL AP	0.48
5	Santa Maria	723940	SANTA MARIA PUBLIC ARPT	0.52
6	Torrance	722950	LOS ANGELES INTL ARPT	0.42
7	San Diego-Lindbergh	722900	SAN DIEGO LINDBERGH FIELD	0.38
8	Fullerton	722976	FULLERTON MUNICIPAL	0.34
9	Burbank-Glendale	722880	BURBANK-GLENDALE-PASSADENA AP	0.39
10	Riverside	722869	RIVERSIDE MUNI	0.42
11	Red Bluff	725910	RED BLUFF MUNICIPAL ARPT	0.5
12	Sacramento	724830	SACRAMENTO EXECUTIVE ARPT	0.51
13	Fresno	723890	FRESNO YOSEMITE INTL AP	0.45
14	Palmdale	723820	PALMDALE AIRPORT	0.57
15	Palm Spring-Intl	747187	PALM SPRINGS THERMAL AP	0.46
16	Blue Canyon	725845	BLUE CANYON AP	0.44

3.4.2.2 ASHRAE 62.2-2016 Ventilation Standard Method (ASH622_2016)

The current ASHRAE 62.2-2016 ventilation standard (referred to as ***ASH622_2016***) builds on the T24_2013 calculation approach described in Equations 5-7, but it adds a superposition adjustment (∅) to account for the sub-additivity of unbalanced mechanical airflows with natural infiltration. Inclusion of superposition reduces the effective infiltration airflow (Q_{inf}, Equation 6) used in mechanical fan sizing when the Whole house fan is unbalanced, as in Equations 8 and 9. This increases the required mechanical airflow.

$$\emptyset = \frac{\mathbf{Q_{inf}}}{\mathbf{Q_{total}}} \tag{8}$$

∅ = sub-additivity factor, 1 if balanced Whole house fan
Q_{inf} = annual effective infiltration airflow, cfm
Q_{total} = target combined natural and mechanical airflow, cfm

$$\mathbf{Q_{fan}} = \mathbf{Q_{total}} - \emptyset(\mathbf{Q_{inf}}) \tag{9}$$

Superposition refers to the sub-additive combining of unbalanced airflows in homes, such as exhaust or supply ventilation fans with natural infiltration. When an unbalanced fan turns on, its airflow does not add directly to the existing infiltration, rather it is sub-additive, so that the resulting total flow is less than the sum of the two individual flows. Unbalanced fans interact with the envelope pressures in the home, shifting the neutral pressure plane vertically, which leads to this sub-additive combination of the fan and infiltration airflows. 50 l/s infiltration flow plus 50 l/s fan airflow does not lead to 100 l/s of house airflow, rather some total airflow less than 100 results. Balanced ventilation fans do not interact with the house pressure balance, so they add simply and directly to infiltration. The standard method for combining these flows historically was quadrature (ASHRAE, 2013; Wilson & Walker, 1990). But recent work has developed new relationships that have been incorporated into ASHRAE 62.2-2016 (Hurel, Sherman, & Walker, 2016). As such, fan sizing in 62.2-2016 can account for this sub-additivity, requiring a larger unbalanced fan than balanced fan. Real-time ventilation rate calculations for equivalence also include this sub-additivity for unbalanced ventilation fans.

3.4.2.3 Adopted 2019 Title 24 Method (T24_2019)

Finally, we include the Whole house fan sizing method that has been adopted in the 2019 code cycle for the Title 24 building energy code (T24_2019). The adopted fan sizing procedure is identical to the ASH622_2016 method described in Section 3.4.2.2, except envelope leakage is treated differently. IAQ fans in homes with envelope leakage greater than 2 ACH50 are sized using a default 2 ACH_{50} envelope leakage value. Homes with reduced envelope leakage below the 2 ACH_{50} limit use the actual leakage rate in fan sizing calculations. So, for very airtight homes, the calculated IAQ fan sizes are identical to those using the ASH622_2016 sizing procedure, while leakier homes have larger fan airflows, because of lower natural infiltration estimates resulting from the default leakage rate of 2 ACH_{50}.

Table 9 Whole house fan sizing methods for Title 24 assessment

Name	Abbreviation Used	Description / Notes	Inputs	Account for Infiltration?	Parameters Included in Infiltration Estimate		
					Envelope Airtightness	Climate Zone and Geometry	Superposition
Fan Ventilation Rate Method	T24_2008	Use floor area and occupancy to calculate fan flow rate based on assumed infiltration (2 cfm per ft^2 floor area). Fan sizing method initially adopted in 2008 T24 Section 4.6.2 of the Residential Compliance Manual. Used as default fan sizing in Performance Path compliance and in prescriptive homes. Most likely compliance path for new homes. Assumed infiltration is roughly correct for homes in the 5-7 ACH_{50} range. More airtight homes will be under-vented.	Floor area; number of bedrooms	No			
Current Builder Practice Method	BuilderPractice	40% is added to the T24_2008 sizing method Whole house fan airflows. This reflects current builder practice based on field studies in California homes. To demonstrate compliance, fans are sized to the T24_2008, but installed airflows are commonly 40% higher, likely due to limitations in available fan airflows on the market (typically 50-80-110 cfm, for example). Builders round up for compliance.	Floor area; number of bedrooms	No			
Target Ventilation Rate Method	Qtotal	Fan sized to the target ventilation rate from the T24_2013 method using floor area and occupancy.	Floor area; number of bedrooms	No			
Total Ventilation Rate Method	T24_2013	Calculate fan flow required to achieve target total ventilation rate using floor area, occupancy and infiltration calculated from blower door measurement of envelope airtightness. Fan sizing method added to T24 in 2013, alongside T24_2008. A small subset of new homes may be complying using this path, especially very airtight homes (e.g., Passive Houses).	Floor area; number of bedrooms; CZ; Airtightness; # of stories	Yes	X	X	
ASHRAE 62.2-2016 Ventilation Standard Method	ASH622_2016	Same as T24_2013, but with the superposition adjustment requiring larger sized unbalanced fans. This is the new default method for calculating mechanical fan size in the 2016 version of ASHRAE 62.2.	Floor area; number of bedrooms; CZ; Airtightness; # of stories; Whole house fan type	Yes	X	X	X
Adopted 2019 Title 24 Method with Adjustment by Fan Type	T24_2019	Same as ASH622_2016, envelope leakage is fixed at 2 ACH_{50} for all cases with leakage greater than 2 ACH_{50}. This leads to larger IAQ fan sizes than calculated with ASH622_2016. Actual envelope leakage is used in cases with leakage below 2 ACH50. Fan flows are identical to ASH622_2016 in these cases.	Floor area; number of bedrooms; CZ; Airtightness; # of stories; Whole house fan type	Yes	X (in cases <2 ACH_{50})	X	X

3.4.3 Calculation of Relative Exposure

The relative exposure for a given time step is calculated from the relative exposure from the prior step (R_{i-1}), the target ventilation rate (Q_{tot}) and the current ventilation rate (Q_i) using Equation 10, unless the real-time or scheduled ventilation is zero, then Equation 11 is used.

$$\mathbf{R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_{tot}\Delta t / V_{space}}} \quad \textbf{(10)}$$

R_i = relative exposure for time-step i
R_{i-1} = relative exposure for previous time-step i-1
Q_{tot} = Total ventilation rate from ASHRAE 62.2-2016 (see Equation 4), cfm
Q_i = Ventilation rate from the current time-step, cfm
Δt = Simulation time-step, seconds
V_{space} = Volume of the space, ft^3

$$\mathbf{R_i = R_{i-1} + \frac{Q_{tot}\Delta t}{V_{space}}} \quad \textbf{(11)}$$

The target ventilation rate, Q_{tot} is calculated using Equation 4. The real-time ventilation rate (Q_i) is the combined airflow of the Whole house fan and natural infiltration, predicted by the REGCAP mass balance model.

4 Results

A total of 960 annual simulations were run using the REGCAP building simulation tool. The parametrically varied parameters included 7 Whole house fan sizing methods, 5 levels of airtightness (0.6, 1, 2, 3, 5), 6 CEC climate zones (1, 3, 10, 12, 13, 16), 2 building prototypes (large, 2-story and medium, 1-story), and 2 fan types (balanced and exhaust). Tabular summaries of energy end-uses, normalized total HVAC energy, Whole house fan airflows, whole house air exchange rates and relative exposure are provided for each of 960 simulations in Appendix B-1 Table 14.

4.1 Raw (not exposure corrected) Results

4.1.1 Weighted Average Exposure and Energy Use Under An Airtightness Requirement in Title 24

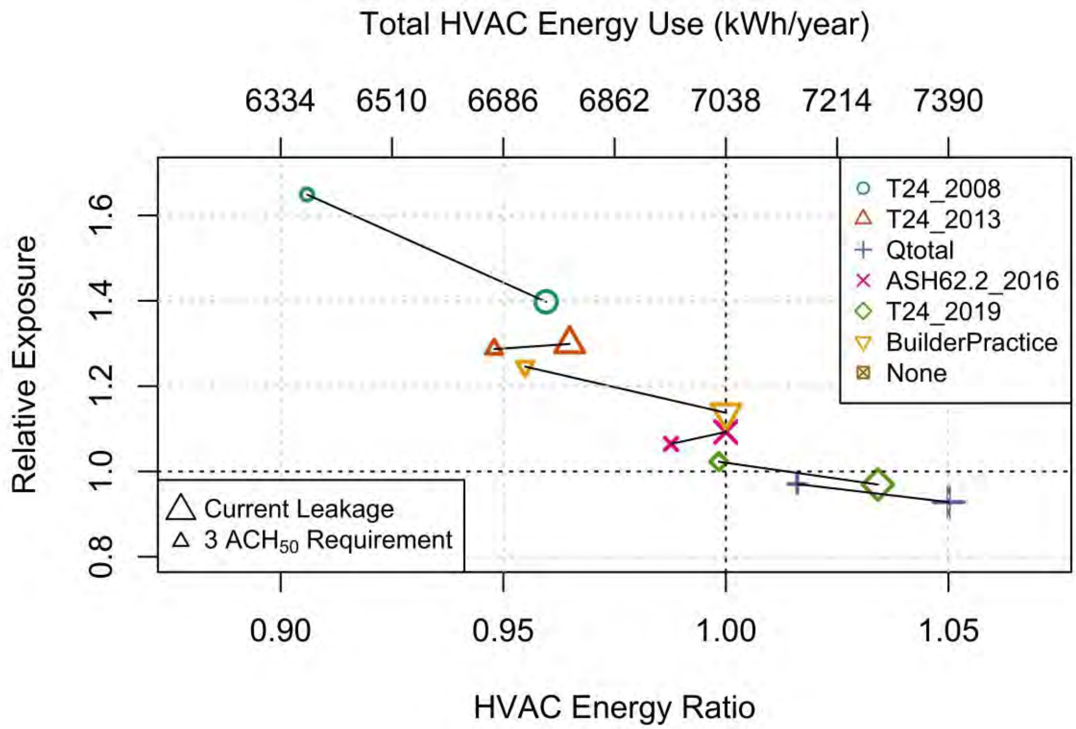
We calculated weighted average IAQ and energy results, based on assigned weightings for the prototype house, climate zone, ventilation fan type and envelope airtightness (see Section 3.2 for details on the applied weights). These were assessed under two scenarios—the current airtightness distribution and a future distribution with a 3 ACH_{50} envelope requirement in the

Title 24 (see airtightness distribution weights in Table 3 from Section 3.2). These weighted average results are summarized in Table 10 and illustrated in Figure 1. Results are further refined by prototype (2-story large vs. 1-story medium homes) in Table 11 to highlight substantial differences between 1- and 2-story homes. We report HVAC energy use in two ways. First, is in absolute kilowatt-hour consumption (referred to as "HVAC Energy Use" in Table 10). Second, we report consumption that is normalized against cases with a Whole house fan sized to the ASH622_2016 method under the current airtightness distribution (referred to as "HVAC Energy Ratio" in Table 10). These estimates allow comparisons between fan sizing methods, as well as between airtightness scenarios for the same fan sizing method or between methods. For example, the T24_2019 fan sizing method has weighted average estimated HVAC savings of 3.6% under an airtightness requirement in the code. This is calculated as the difference between current and future HVAC Energy Ratio Values (1.034 – 0.998 = 0.036). Similarly, we can compare weighted average HVAC energy use under the current Fan Ventilation Rate Method (T24_2008) with the newly adopted T24_2019 sizing method. The new adopted fan sizing will increase estimated HVAC energy use by 7.4% (0.960 – 1.034 = -0.074), and will reduce exposure by 43% (1.40 – 0.97 = 0.43).

Table 10 Weighted average relative exposure, ventilation energy and HVAC energy, with current airtightness and under potential future airtightness requirement.

Fan Sizing Method	Relative Exposure			HVAC Energy Use (kWh/year)			HVAC Energy Ratio		
	Current	Future	Change	Current	Future	Savings	Current	Future	Savings
T24_2008	1.40	1.65	25%	6754	6376	378	0.960	0.906	5.4%
T24_2013	1.30	1.29	-1%	6791	6672	119	0.965	0.948	1.7%
Qtotal	0.93	0.97	4%	7390	7151	239	1.050	1.016	3.4%
ASH62.2_2016	1.09	1.06	-3%	7038	6951	87	1.000	0.988	1.2%
T24_2019	0.97	1.02	5%	7279	7027	252	1.034	0.998	3.6%
BuilderPractice	1.14	1.25	11%	7039	6721	318	1.000	0.955	4.5%
None	2.75	4.20	155%	6126	5735	391	0.870	0.815	5.6%

Figure 1 Weighted average population level HVAC energy and relative exposure when airtightening new California homes under different fan sizing methods. Small symbols are the future, airtightened results, and the large symbols are the existing results.



Overall, our results show that none of the Whole house fan sizing methods are perfect, and that all of them have weighted average relative exposure either above or below 1.0 under both current and future airtightness weightings. In the presence of Whole house fan ventilation, a new airtightness limit in the Title 24 would lead to relatively marginal whole house HVAC energy savings of 1-5% of total HVAC consumption (averaging roughly 100 to 300 kWh/year). The magnitude of these effects and the change in relative exposure depend on the fan sizing method and house prototypes, as discussed below. The greatest savings are for the fan sizing methods that do not vary Whole house fan sizing by airtightness (T24_2008, T24_2019, Qtotal and BuilderPractice). Notably, T24_2019 does increase the required fan size in cases with leakage below 2 ACH_{50} (i.e., the 0.6 and 1 ACH_{50} cases), but the weighting factors for these cases amount to only 6% of total weight. These sizing methods do not increase the required Whole house fan airflow in response to increased airtightness. When fan sizes remain constant and infiltration is reduced, HVAC energy and ventilation rates are reduced while exposure increases. In Figure 1, these cases have lines that slope up and to the left, indicating reduced HVAC energy use and increased relative exposure. For fan sizing methods that use infiltration adjustment (ASH62.2_2016 and T24_2013), the airtightness savings are still larger than the increased ventilation energy, but net-savings are small (roughly 1%). These methods maintain relative exposure very close to one, rather than increasing it. In Figure 1, these cases have short lines tracking slightly down and to the left, indicating small HVAC energy savings and very slightly reduced exposure.

Under a hypothetical 3 ACH_{50} airtightness requirement, the infiltration-adjusted sizing methods have larger fan airflows and slightly reduced exposure (and increased energy use), while the other fan sizing methods have the same fan airflows and increased exposure (and reduced energy use). The cases with no Whole house fan have the worst exposure under an airtightness requirement (4.37), which illustrates the necessity of Whole house fan ventilation as homes become more airtight. This equates to more than a quadrupling of contaminant concentrations in non-mechanically ventilated homes. The only fan sizing method with weighted average exposure below 1.0 under a 3 ACH_{50} airtightness requirement was the Qtotal method (0.97), whose exposure was also below 1.0 under current airtightness weightings. All other fan sizing methods have weighted average exposure above 1.0 under an airtightness requirement. Of these methods, those that are closest to 1.0 are the T24_2019 and ASH622_2016 methods (1.02 and 1.06, respectively), with energy savings associated with airtightening of 3 and 1%, respectively. The T24_2013 method would have lower exposure under the airtightness requirement, though still greatly above 1.0 (at 1.29). All other sizing methods have similarly high exposure under the airtightness requirement, generally falling in the 20 to 60% worse range (for BuilderPractice (1.25) and T24_2008 (1.65)). This worsened IAQ buys these cases roughly 5% total HVAC energy savings from airtightening relative to current airtightness weightings.

Based on these results, the T24_2019 fan sizing method has the weighted average exposure closest to 1.0 with both current and future airtightness weightings (at 0.97 and 1.02). The two closest competitors that maintain exposure close to 1.0 under both airtightness weighting are the current ASH622_2016 and the Qtotal methods. The ASH622_2016 method has consistently higher exposure (at 1.09 and 1.06), while the Qtotal method has consistently lower exposure (at 0.93 and 0.97). Under current airtightness weights, the T24_2019 and Qtotal methods increase energy use by 3 and 5% relative to the ASH622_2016 method (and by 1 and 3% under future airtightness weights). The difference in weighted average total consumption between any of these three sizing methods is roughly 350 kWh/year (though absolute kWh differences are greater in harsher climate zones).

Performance was substantially affected by house prototype, so we also show the weighted averages disaggregated by prototype house in Table 11. The differences are due to the different number of stories and increased infiltration rates with the 2-story homes. Overall, weighted average savings from airtightening are much higher for the 2-story large prototypes, between 3 and 7% (200 to 500 kWh/year) across all fan sizing methods. In contrast, the 1-story medium homes average only 0 to 3% (roughly 0 to 200 kWh/year) savings across fan sizing methods.

Table 11 Weighted average relative exposure and HVAC energy, by fan sizing method and house prototype, with current airtightness and under potential future airtightness requirement.

Fan Sizing Method	Prototype	Relative Exposure			HVAC Energy Use (kWh/year)			HVAC Energy Ratio		
		Current	Future	Change	Current	Future	Savings	Current	Future	Savings
T24_2008	2-story	1.28	1.59	30%	7193	6684	509	0.972	0.903	6.9%
	1-story	1.54	1.73	19%	6218	5999	218	0.943	0.910	3.3%
T24_2013	2-story	1.26	1.32	6%	7149	6921	228	0.966	0.935	3.1%
	1-story	1.35	1.25	-10%	6354	6367	-14	0.964	0.966	-0.2%
Qtotal	2-story	0.90	0.97	6%	7834	7470	364	1.058	1.009	4.9%
	1-story	0.96	0.98	2%	6848	6761	87	1.038	1.025	1.3%
ASH62.2 _2016	2-story	1.08	1.08	0%	7402	7214	187	1.000	0.975	2.5%
	1-story	1.11	1.04	-7%	6594	6630	-36	1.000	1.005	-0.5%
T24_2019	2-story	0.95	1.03	8%	7699	7310	388	1.040	0.988	5.2%
	1-story	0.99	1.01	2%	6765	6681	84	1.026	1.013	1.3%
Builder Practice	2-story	1.08	1.24	16%	7481	7020	461	1.011	0.948	6.2%
	1-story	1.21	1.26	5%	6499	6355	143	0.986	0.964	2.2%
None	2-story	2.25	3.43	117%	6508	6001	507	0.879	0.811	6.9%
	1-story	3.36	5.14	178%	5659	5410	249	0.858	0.820	3.8%

4.1.2 Relative Exposure

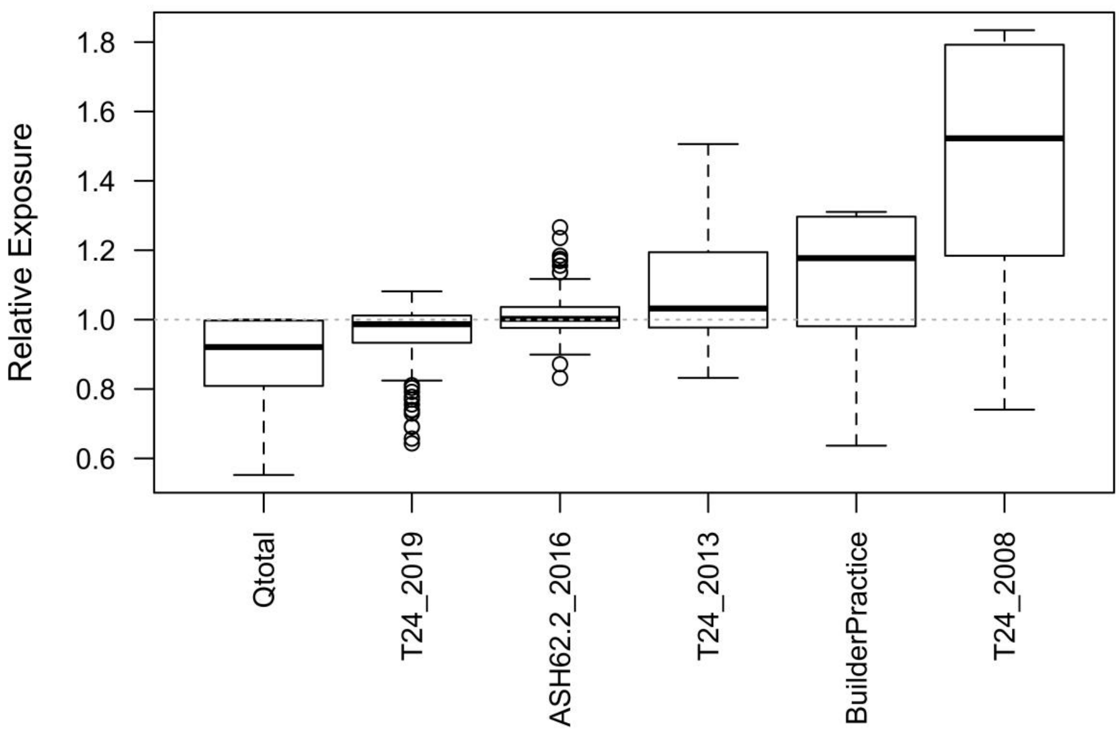
From an IAQ perspective, the relative exposure is the primary outcome of this work. As noted above, the fan sizing methods are imperfect and none achieved weighted average exposure equal to 1.0 and most of them had higher exposures. In addition to weighted averages, the distributions of relative exposure values are also critical. It is desirable for exposures to be tightly clustered around the mean value of 1.0, which ensures the homes are neither under- nor over-ventilated, which limits either poor IAQ or increased energy consumption.

We show how relative exposure distributions change with fan sizing method in Figure 2[2]. The ASHRAE 62.2-2016 fan sizing method, which accounts for all factors affecting infiltration, as

[2] In the boxplots in this report the middle bar represents the median, the boxes the 25th and 75th percentile, the whiskers are range. The circles/dots represent outliers that are more than one and half times the interquartile range from the median.

well as fan type (balanced vs. exhaust), has the tightest distribution of relative exposures and averages close to 1.0. The T24_2019 sizing method is also tightly clustered, with slightly greater variance. The outlier cases with low exposure when using T24_2019 are the 3 and 5 ACH_{50} homes whose fans are sized assuming envelope leakage of only 2 ACH_{50}. This results in higher air flow IAQ fans resulting in lower exposure and higher energy use. All other sizing methods have the potential to substantially under- or over-ventilate any given home, depending on its location, airtightness, prototype and fan type because they do not account for these interactions. Variability was greater when using the other sizing methods that did not include a sub-additivity adjustment for unbalanced fans.

Figure 2 Boxplots of annual relative exposure, by fan sizing method.



Air exchange rates and relative exposure aggregated by airtightness and fan sizing method are compared in Figure 3 and Figure 4. These figures show trends averaged over house prototype, fan type and climate zone. We then assessed individual cases and the relationship between fan sizing method, house prototype, fan type, airtightness and exposure. Figure 5 shows these case-by-case results for CZ10 (Riverside). Climate zone does not substantially affect any of the patterns and trends with airtightness, or comparisons across fan sizing methods, so we use CZ10 as a frame for discussion (other climate zone plots are provided in the Appendix B-1 Figure 15 through Figure 19).

Figure 3 Mean air exchange rates by envelope airtightness and fan sizing method, aggregated across prototype, fan type and climate zone.

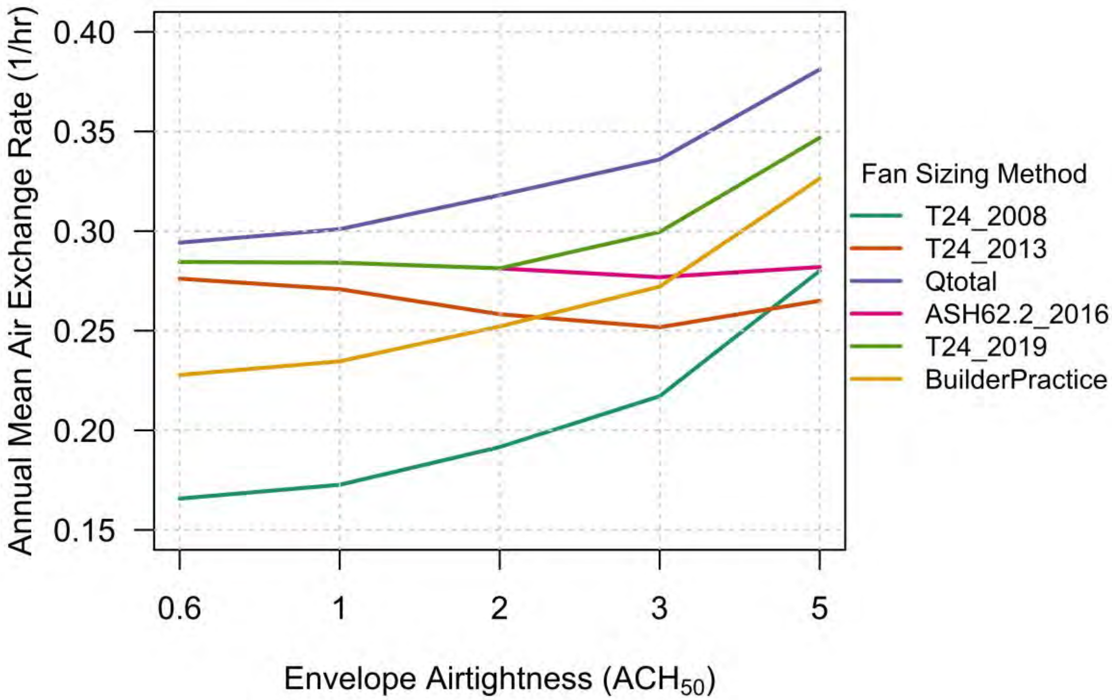


Figure 4 Mean relative exposure by envelope airtightness and fan sizing method, aggregated across prototype, fan type and climate zone.

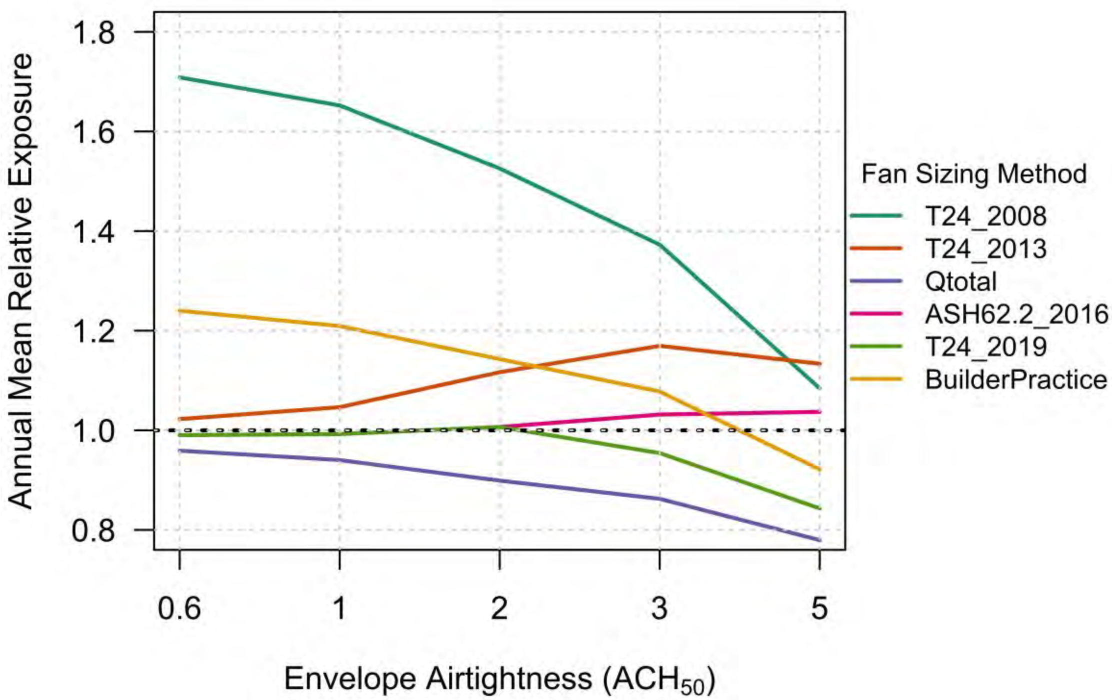
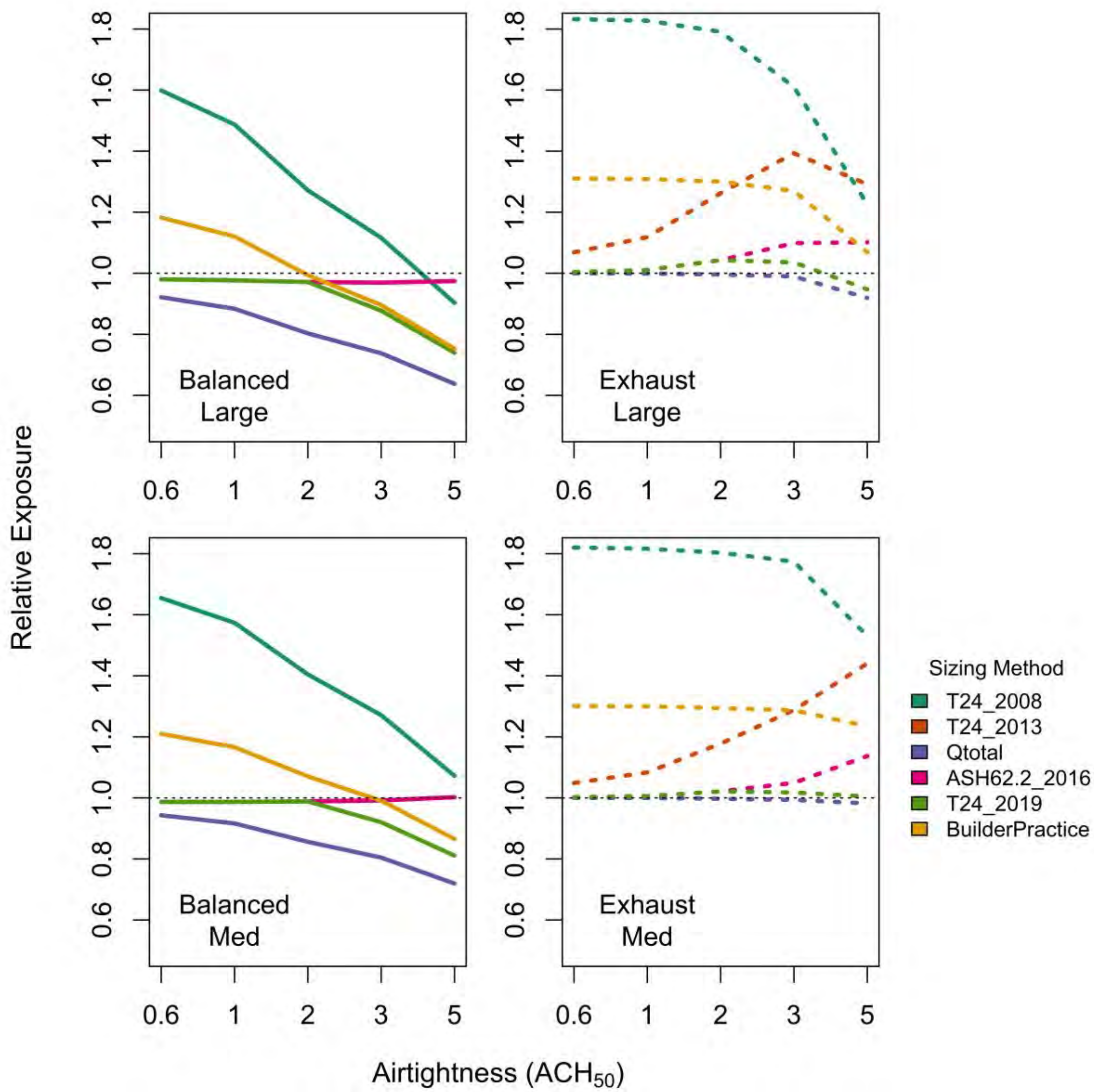


Figure 5 Variability of relative exposure with airtightness in CZ10, by prototype, fan type and fan sizing method.



These results show the following trends: (1) exposure is reduced (and ventilation rates increase) as air leakage increases, (2) the ASH622_2016 sizing method provides the most consistent exposure across these factors, (3) exhaust fans have higher exposure than balanced fans, (4) for exhaust fans sized using fixed airflow methods, there is little change in exposure between 0.6 and 3 ACH_{50}, and (5) exposure is higher in 1-story medium prototype homes.

For most fan sizing methods, this inconsistency translates to either unnecessarily high energy use or pollutant exposure for the occupants. For the majority of fan sizing methods and fan types, relative exposure goes down as air leakage increases, with the 5 ACH_{50} cases generally having the lowest exposure (and highest ventilation rates and energy use).

Balanced fan cases have overall lower exposure compared to exhaust fans because balanced fans simply add to infiltration while exhaust fans are sub-additive resulting in higher air flows for homes with balanced fans. For fixed airflow sizing methods using balanced Whole house fans (T24_2008, Qtotal, T24_2019, and BuilderPractice), increasing air leakage leads to higher ventilation rates and reduced exposure. As a result, exposure varies widely above and below 1.0 depending on leakage. The infiltration adjusted sizing methods (ASH622_2016 and T24_2013) are flat across airtightness levels with balanced Whole house fans, because they reduce Whole house fan airflow in response to increased infiltration estimates. These results again illustrate that the current ASH62.2_2016 sizing method has the most consistent relative exposure—neither under- nor over-ventilating the homes. For exhaust fans, the 2019 proposed sizing method with sub-additivity (T24_2019) and the Qtotal sizing methods provide exposure most consistently at or below 1.0, though this consistency falls apart in balanced fan cases, where the fixed airflow sizing methods either strongly under- or over-ventilate the homes.

For exhaust fan cases all sizing methods that don't scale with envelope leakage are under-ventilating the home relative to the ASHRAE standard target airflow. The worst of the sizing methods is the current default method used in Title 24 compliance—T24_2008 fan ventilation rate method—with exposure 50-80% higher in this climate zone. For fixed airflow sizing methods, there is little change in exposure (or ventilation rates) between 0.6 and 3 ACH_{50}. In the 1-story exhaust fan cases, there is not even substantial change when at 5 ACH_{50}. In these exhaust fan cases, the whole house airflows are fully dominated by the mechanical exhaust fans, and natural infiltration contributes almost no airflow. As a result, changing leakage area does not affect ventilation rates, exposure or energy use.

4.1.3 HVAC Energy Savings from Increasing Airtightness

From an energy perspective, there is a benefit to reducing the ventilation rates in homes and increasing relative exposure (and worsening IAQ), as has traditionally been done when air sealing homes. Yet, even for cases with the same exposure, we expect the airtightening of homes to save energy, because airtightening and mechanically ventilating shifts ventilation airflows to mild weather periods, and it reduces the annual average airflow required for a given exposure target (see Section 2.2). This time-shifting will have the most impact in locations with the harshest weather conditions. These effects of changing ventilation rates and exposure (IAQ), as well as changing when ventilation occurs and how much is needed, interact to determine changes in energy consumption from airtightening with mechanical ventilation. For some cases, these effects will interact additively to increase savings, and in others, we expect these effects to cancel out to some extent, limiting potential savings.

All fan sizing methods are imperfect. As a result, when changing airtightness, the ventilation rate and relative exposure are also changed. This is critical when assessing energy savings from airtightening because the IAQ is different between the cases. The fixed airflow fan sizing methods make no attempt to account for these changes with air leakage, while the infiltration-adjusted sizing methods try (albeit imperfectly) to maintain similar ventilation rates and exposure in all homes.

In fixed airflow sizing methods, balanced fans have much higher exposure and lower ventilation in more airtight cases (compared with balanced fans in leakier homes), so saving energy through airtightening is straightforward, albeit at the cost of poorer IAQ. Fixed airflow exhaust fan cases also tended to have higher exposure (and lower ventilation rates) at lower leakage levels, but this was static between 0.6 and 3 ACH_{50}, and in some 1-story cases, it remained static up to 5 ACH_{50}. As noted before (and discussed in Section 4.3), these cases were strongly mechanical fan dominated, such that natural infiltration contributed almost no additional airflow. As a result, changing the airtightness did not change ventilation rates, exposure or energy use. These cases may show some energy savings by going from 5 to 3 ACH_{50}, but very little for further tightening.

For infiltration-adjusted sizing methods, balanced fans had very little variability in ventilation rates or exposure across airtightness levels. Exposure was in fact very slightly lower (higher ventilation rates) in the most airtight cases. This same pattern was generally true for infiltration-adjusted exhaust fan cases, where the highest exposure (and lowest ventilation rates) were in the leakiest homes. For both exhaust and balanced fans sized with infiltration-adjustment, we expect that airtightening will reduce exposure and actually increase ventilation rates, which will counteract the potential energy savings from time-shifting ventilation to milder periods.

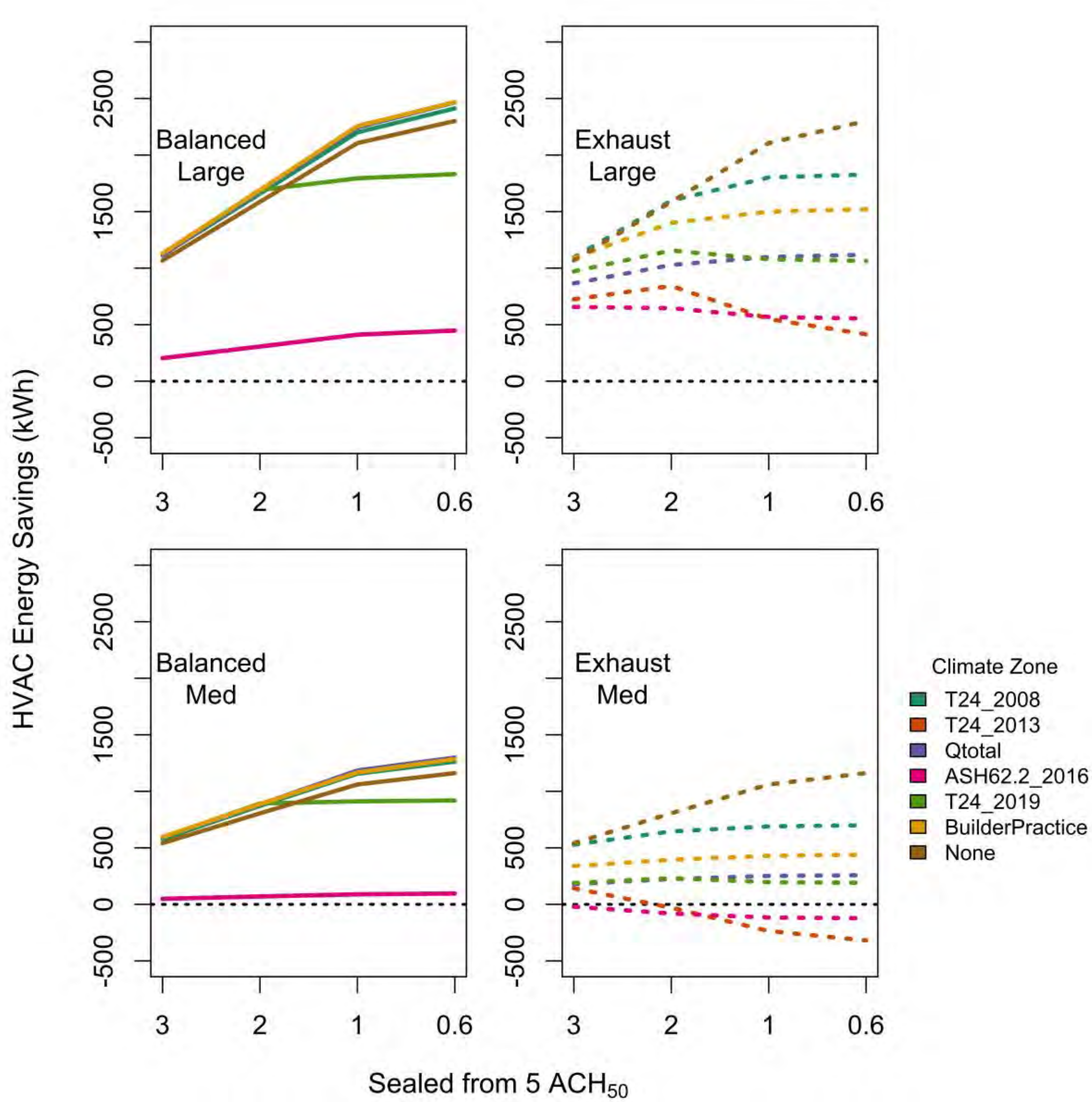
Consistent with these observations, the weighted average results in Section 4.1 suggest that marginal annual HVAC savings on the order of 1-5% can be expected if a 3 ACH_{50} or less airtightness requirement were included in the Title 24 for new homes. A distinction was seen between fan sizing methods that adjusted fan size by airtightness, climate zone and fan type, compared with fixed airflow methods, where fan size is independent of house airtightness. The fixed airflow sizing methods had higher weighted average HVAC savings of 3 to 5% (and generally higher occupant exposure), while the variable fan sizing methods had very low savings of roughly 1% (but reduced exposure marginally).

These weighted average results are useful for a statewide assessment of priorities, but we are also interested in the impacts of airtightening individual homes, which we expect will align with the trends in exposure discussed above. First, we average the results across climate zones and show the potential savings for each fan sizing method in Figure 6. Overall, the predicted savings from air leakage reductions increases as fan airflows get smaller. So, savings are generally greatest in cases with no IAQ fan ventilation, followed by the under-vented T24_2008, then BuilderPractice, etc. In these cases, predicted energy savings grow as leakage is incrementally reduced down to 0.6 ACH_{50}. As fan sizes increase, the whole house airflows become more fan dominated, and there is less impact from changing background envelope leakage levels. The fan sizing methods that account fully for infiltration in fan calculations have limited energy savings from air sealing, and the savings are often static or reduced as envelope leakage is tightened below 3 ACH_{50}.

Second, we show results for individual cases (with no averaging). For each unique combination of airtightness, climate zone and fan type, we assessed the annual energy savings of tightening from a baseline of 5 ACH_{50} to the reduced airtightness levels (3, 2, 1 and 0.6 ACH_{50}). The no fan cases are plotted in Figure 7 (Section 4.1.3.1) to show the impacts of airtightening without mechanical ventilation. To illustrate the impact of Whole house fans on airtightening savings , the ASH62.2_2016 and the T24_2019 cases are shown in Figure 8 and Figure 9 (Sections 4.1.3.2 and 4.1.3.3), respectively. All other fan sizing methods are plotted in the Appendix B-1 Figure 20 through Figure 23.

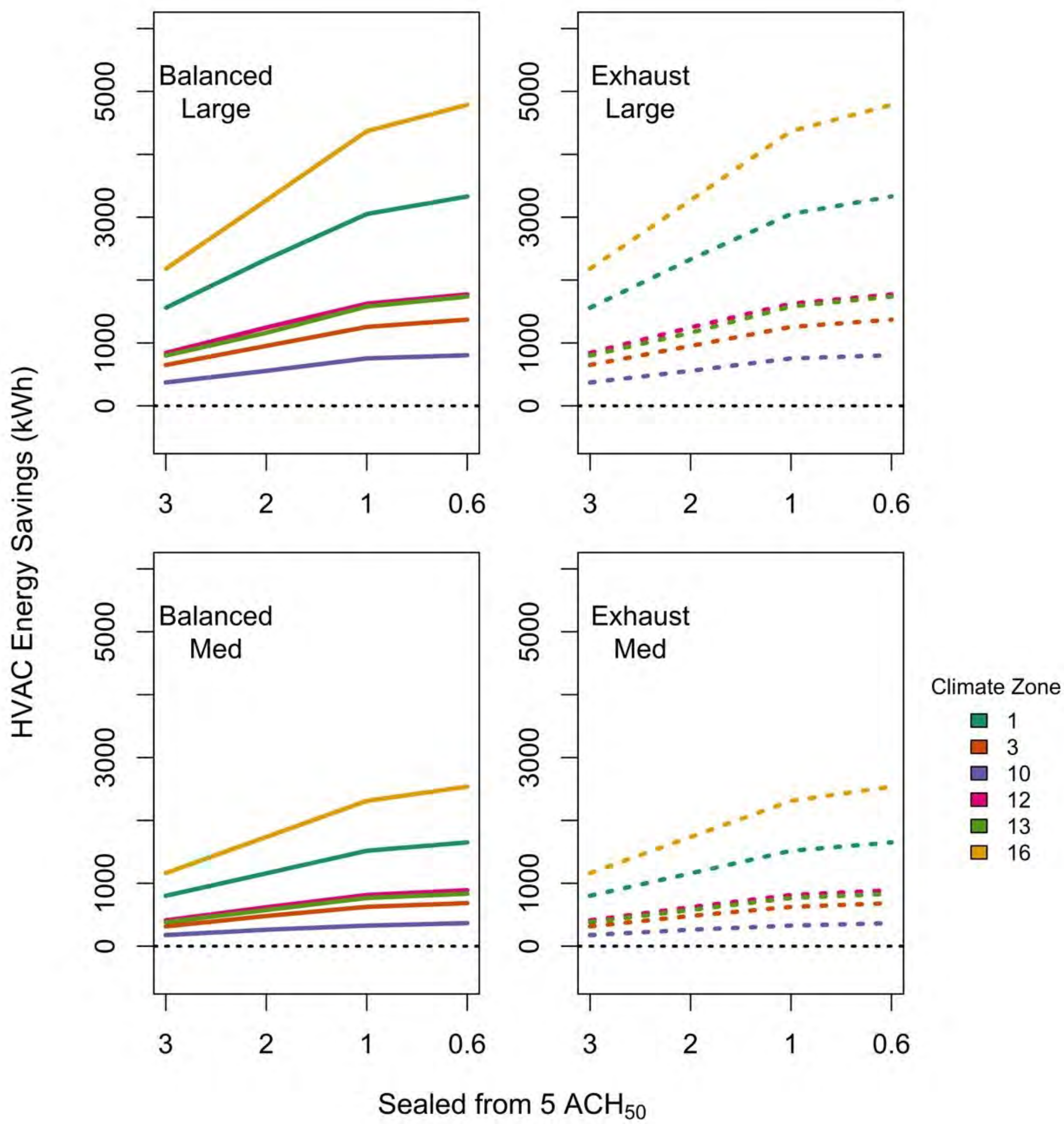
Finally, we present energy savings estimates that are normalized based on all cases having an exposure of 1.0 (i.e., the same IAQ), in an attempt to isolate the impacts of airtigthtening while providing equivalent IAQ (see Section 4.2). Both raw and normalized HVAC energy savings estimates when sealing from 5 ACH_{50} are tabulated for each case and airtightness target in Appendix Table 15.

Figure 6 All cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}. Results averaged across climate zones.



4.1.3.1 No Whole house fan Airtightness Savings

Figure 7 No fan cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

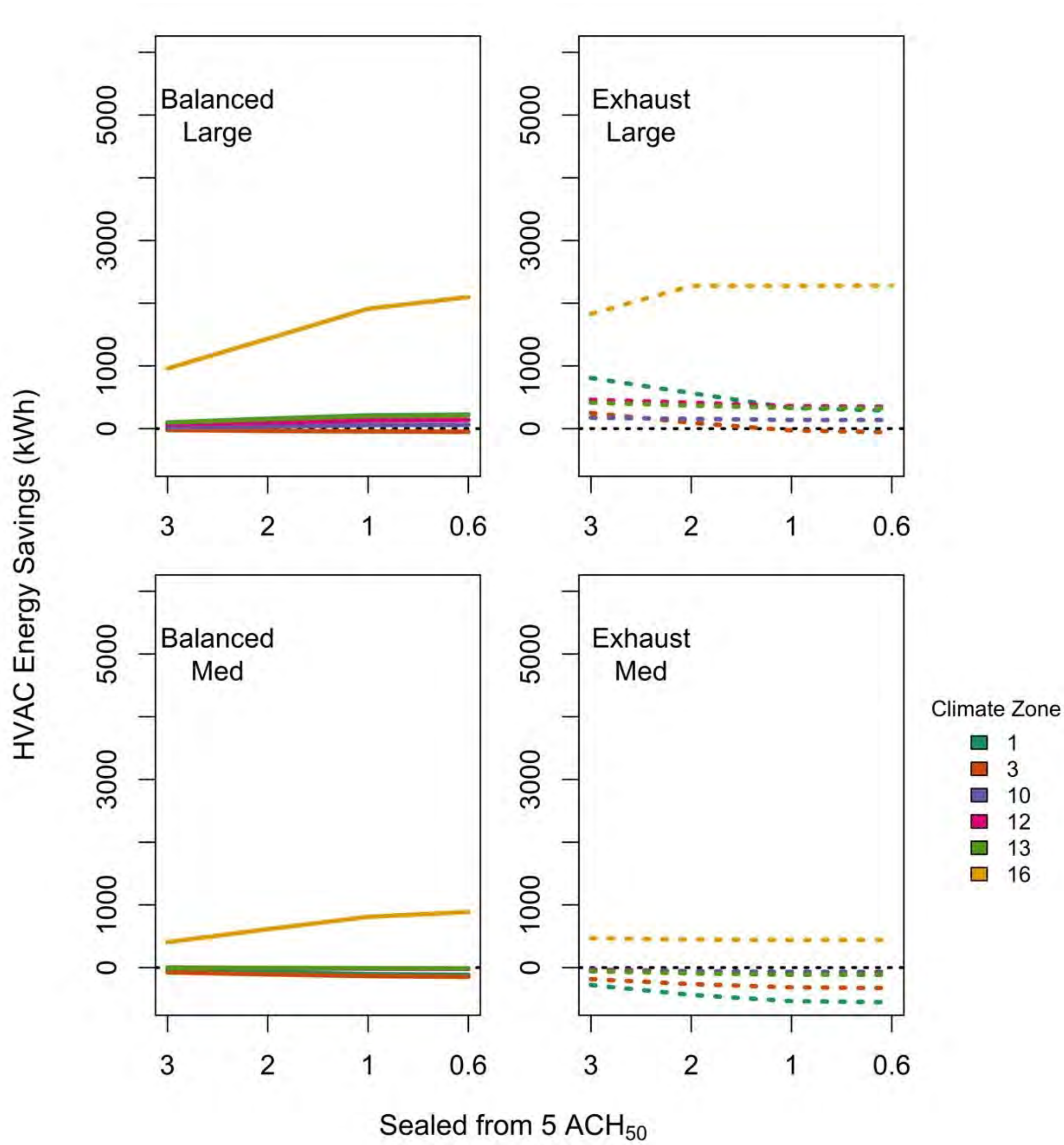


With no Whole house fan, most climates showed substantial energy savings from increased airtightness, and savings increased incrementally as homes became more airtight. The predicted energy savings are much greater in the 2-story large prototype homes than in their 1-story counterparts, irrespective of fan sizing method (or presence of a Whole house fan). This is consistent with the weighted average results in Table 11.

Savings varied from roughly 200-5,000 kWh/year, with strong climate zone and house prototype effects. Far and away, the greatest savings from airtightening accrued in the coldest locations—Blue Canyon CZ16 and Arcata CZ1. The lowest savings were in CZ10 (Riverside), while the other Central Valley and Bay Area climates were in the middle. Note: in the no fan cases, the 'balanced' and 'exhaust' figures are identical, because there are no fans.

4.1.3.2 ASH622_2016 Airtightness Savings

Figure 8 ASH62.2_2016 cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

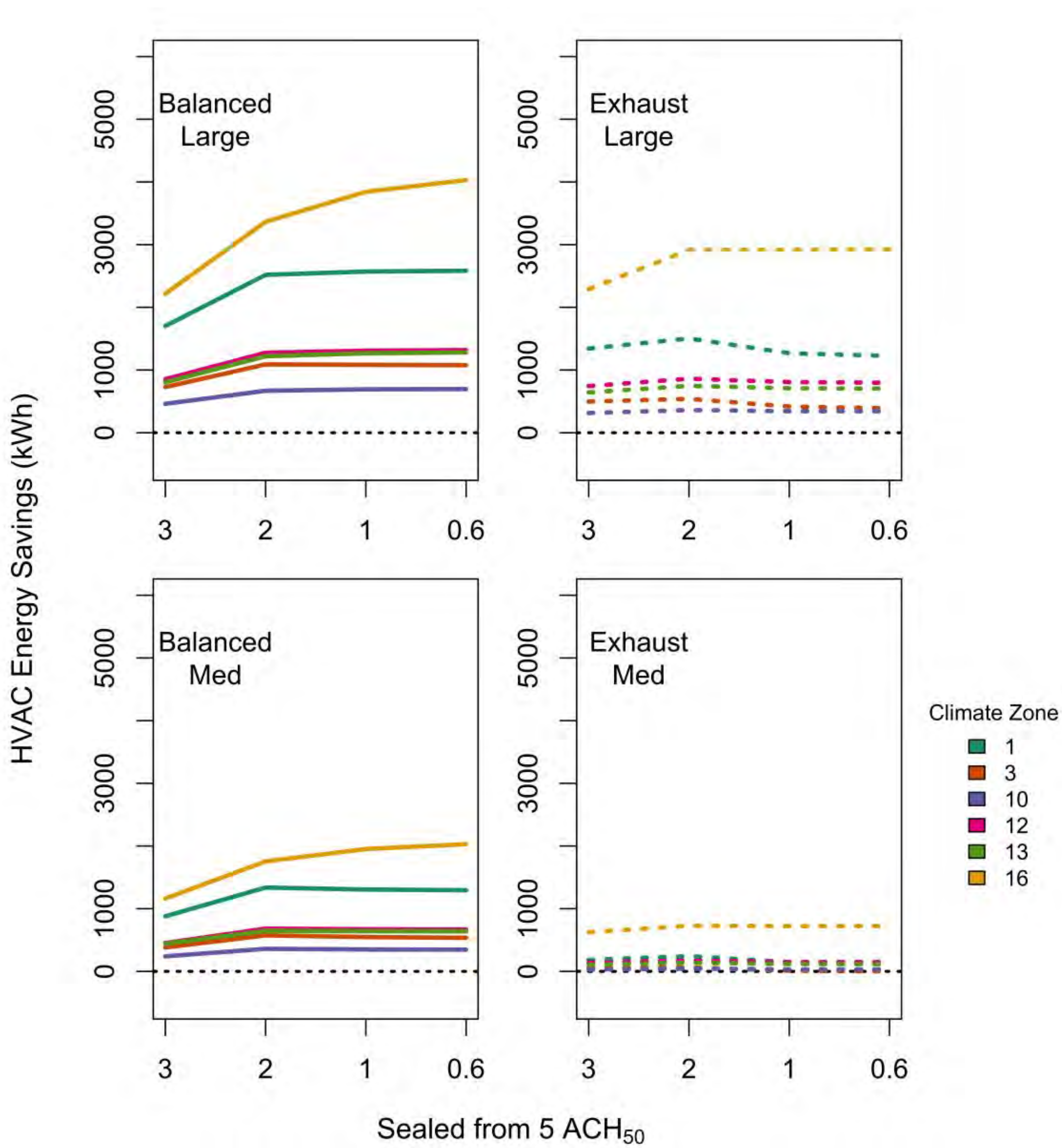


Adding ventilation fans sized according to ASH62.2_2016, which includes infiltration and fan type adjustments (Figure 8) shows much lower savings or increased consumption with airtightening and only CZ16 has appreciable savings. This is because the ASHRAE sizing approach tends to keep total air flows the same with climate and airtightness changes.

For the exhaust fan cases there are changes with airtightness that are greatest in CZ16. This is the result of imperfections in the fan sizing method on ASHRAE 62.2-2016.

4.1.3.3 T24_2019 Airtightness Savings

Figure 9 T24_2019 cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



In Figure 9, we show the energy savings due to airtightening when the fans are sized using the proposed 2019 sizing method plus a sub-additivity adjustment for unbalanced fans (T24_2019). The fan airflows for these cases do not change with airtightness, with the exception of the cases below 2 ACH_{50}, whose IAQ fan airflows are increased as in ASH622_2016. In the homes with envelope leakage greater than 2 ACH_{50}, the envelope is fixed at 2 ACH_{50}, which leads to oversized fans in leaky homes. Since the fan airflows do not change with air leakage, the only change is reduced natural infiltration, which saves energy.

Here there are much larger savings in the balanced fan cases, and substantial savings for the exhaust fans in 2-story, large prototype homes with no increased consumption for any of the prototypes or climate zones. This is expected based on the exposure and ventilation results for this sizing method, because as homes become progressively more airtight, their ventilation rates go down and exposure increases. We also observe that for exhaust fan cases, energy savings do not increase with further airtightening beyond 3 ACH_{50}. As noted in the exposure section, ventilation rates and exposure were nearly static across these airtightness levels when using exhaust fans, such that reducing envelope leakage area had very little effect on the home's ventilation rate. Since reducing leakage areas only very marginally reduced ventilation rates, little additional energy savings are recorded beyond 3 ACH_{50}. In the harshest climates and in 2-story homes, we see some increasing savings with further airtightening, which is likely the result of shifting ventilation airflows to milder weather periods.

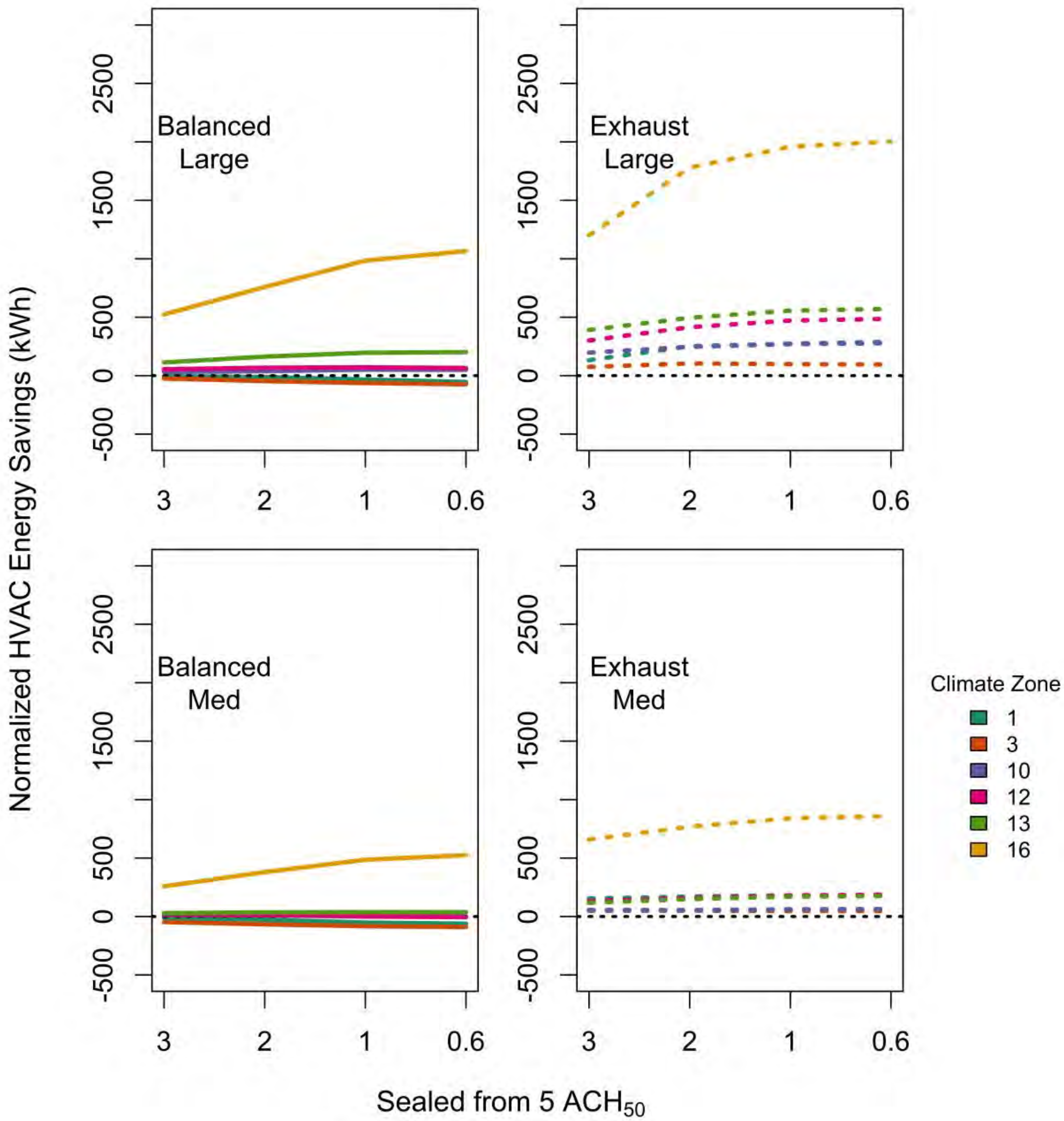
4.2 Exposure-Normalized Airtightness Savings

The raw results in Section 4.1.3 showed that the impacts of airtightening continuously ventilated new California homes depend greatly on fan sizing method, number of stories in the home, fan type and climate zone. Yet, it is critical to note that the air exchange rates and relative exposures were not the same for these cases. When reducing air leakage, the exposure was also changing. Due to differences in exposure and ventilation rates across levels of airtightness, fixed airflow cases tended to consistently save energy by reducing ventilation and increasing exposure, while infiltration-adjusted cases sometimes saved and sometimes increased energy consumption.

To account for these differences in exposure we normalized annual HVAC energy use by relative exposure, treating each individual case as if its relative exposure averaged precisely 1.0. The goal is to identify the benefits of airtightening, if all cases were providing the same service (i.e., identical annual average exposure/IAQ).

The normalized HVAC energy savings from airtightening is shown for the ASH62.2_2016 sizing cases in Figure 10 (normalized HVAC savings for all other fan sizing methods are plotted in Appendix B-1 (Figure 24 through Figure 27). With the exception of CZ16, the resulting energy savings were very small (typically 200 kWh or less). Nearly all cases of increased consumption were eliminated. For this sizing method, the raw, unormalized results were close to 1.0, so normalization had fairly small impacts on energy savings estimates attributable to air sealing for the ASHRAE 62.2-2016 sizing method. This was not the case for other sizing methods, where exposure corrections were larger and previously inflated savings were reduced. As was the case with the raw results, CZ16 is the only location with substantial normalized energy savings resulting from an airtightness requirement. Normalized energy savings are still greater in the 2-story prototypes, and exhaust fan savings are marginally higher than for balanced fans.

Figure 10 ASH62.2_2016, Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



In Figure 11, we compare mean raw and normalized HVAC energy savings by climate zone and house prototype for sealing from 5 to 3 ACH_{50}. These values are averaged across the different fan sizing methods. The normalization of energy savings by relative exposure reduced energy savings substantially. This suggests that for most cases, the vast majority of energy savings presented in Sections 4.1.3.1 through 4.1.3.3 resulted from worsened IAQ (higher exposure) in the more airtight cases.

When energy is normalized by relative exposure, energy savings from a 3 ACH_{50} airtightness requirement in Title 24 are generally very low (i.e., <200 kWh/year), irrespective of fan sizing method. Climate zone 16 is the sole exception where substantial savings remain after normalization, though these savings are less than half those predicted from the raw simulation results.

Normalized energy savings distributions are provided for each climate zone in Figure 12, which again confirm that CZ16 is the only location with substantial normalized savings potential when sealing to 3 ACH_{50}. This is because CZ16 is the coldest location, which means the shifting of ventilation toward mild weather periods has a major impact. In the milder zones of the state, the impact of this seasonal shifting is quite small. In climate zones other than CZ16, the maximum normalized HVAC savings from airtightening to 3 ACH_{50} was less than 400 kWh/year. Normalized savings distributions are also provided by target airtightness level in Figure 13, which confirms that normalized HVAC energy savings increase very modestly with each incremental reduction in envelope leakage. Despite this marginal increase, and with the exception of the harshest climates, there is little normalized savings for airtightening home envelopes to anywhere from 3 to 0.6 ACH_{50}. Even when sealing from 5 to 0.6 ACH_{50}, more than 75% of the cases have normalized HVAC energy savings less than 500 kWh/year.

Figure 11 Comparison of median raw and normalized HVAC energy savings for sealing from 5 to 3 ACH_{50}, aggregated by climate zone and house prototype. Medians include all fan sizing methods and fan types.

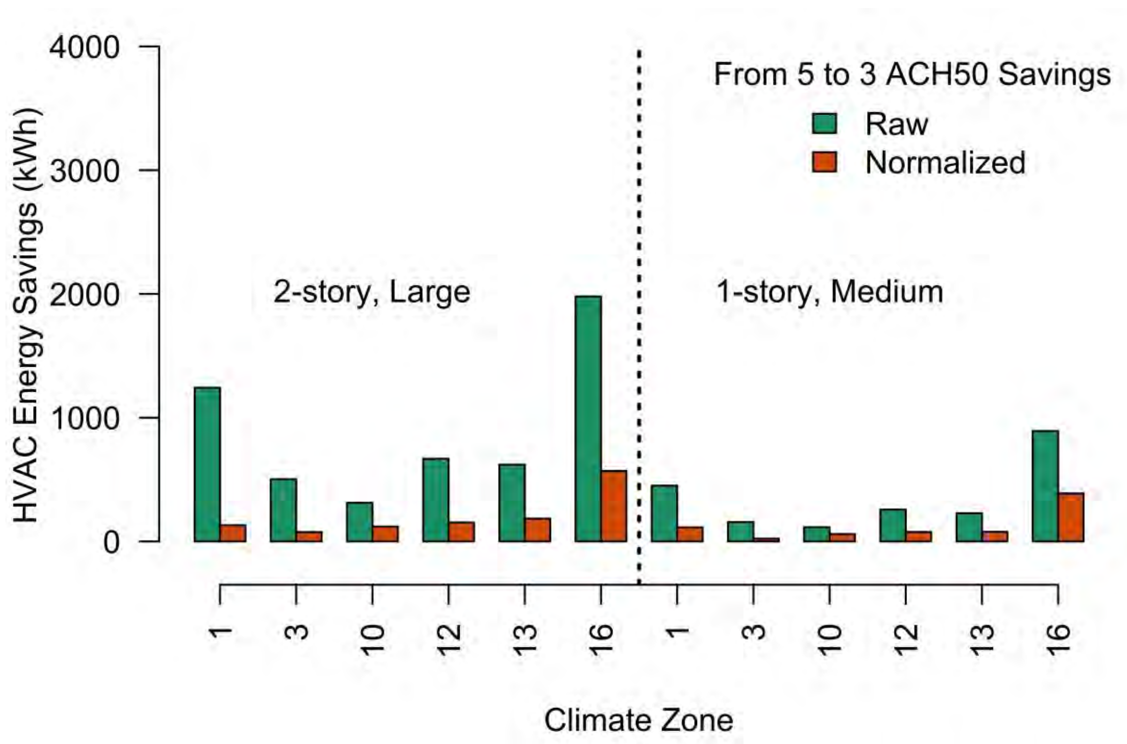


Figure 12 Distributions of normalized HVAC energy savings by climate zone, when sealing building envelope from 5 to 3 ACH_{50}.

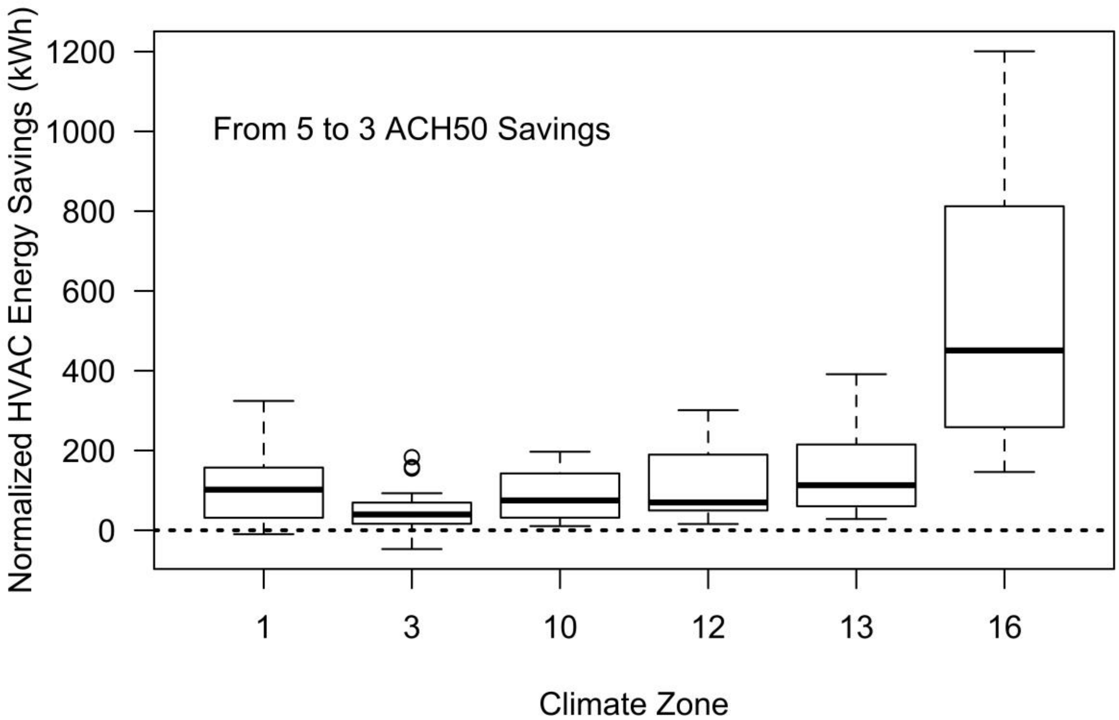
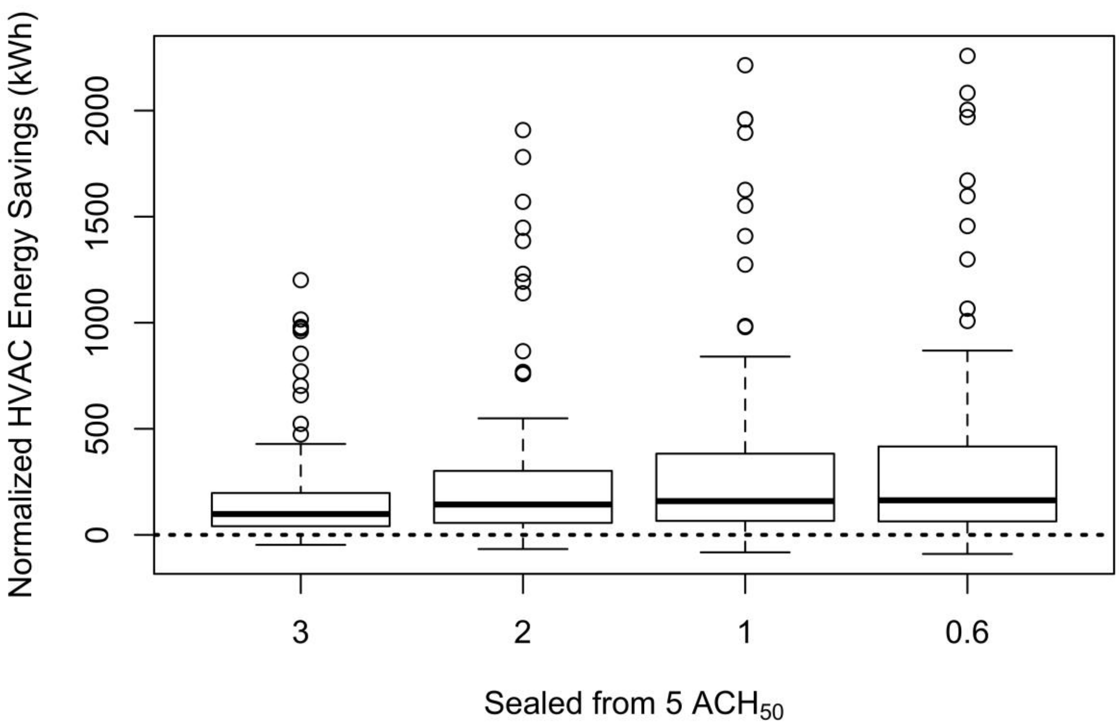


Figure 13 Distributions of normalized HVAC energy savings by airtightness, when sealing building envelope from 5 to 3, 2, 1 or 0.6 ACH_{50}.



4.3 Sub-Additivity and Infiltration in REGCAP and ASHRAE 62.2-2016

In the prior sections, we have established how balanced and exhaust fans perform very differently in terms of exposure, ventilation and energy use across fan sizing methods. The two most notable issues were as follows: (1) weighted average exposure for the ASHRAE 62.2-2016 sizing method was 1.1 (instead of 1.0), varying from 0.8 to 1.2, even though the method accounts for infiltration and fan type; and (2) fixed airflow sizing methods had nearly unchanging exposure, ventilation rates and energy use across envelope leakages from 0.6 to 3 ACH_{50} in 2-story homes and from 0.6 to 5 ACH_{50} in 1-story homes.

After an examination of factors affecting predicted infiltration rates in REGCAP and in ASHRAE 62.2-2016 (see Appendix B-1), we have determined that these results are due to the sub-additive combination of mechanical and natural airflows. For the first issue, differences in weather, envelope leakage distributions and the use of the simplified linearized approach to sub-additivity calculations in the ASHRAE fan sizing calculations leads to exposures not being equal to 1. The second factor is the result of how unbalanced natural infiltration combines with mechanical ventilation.

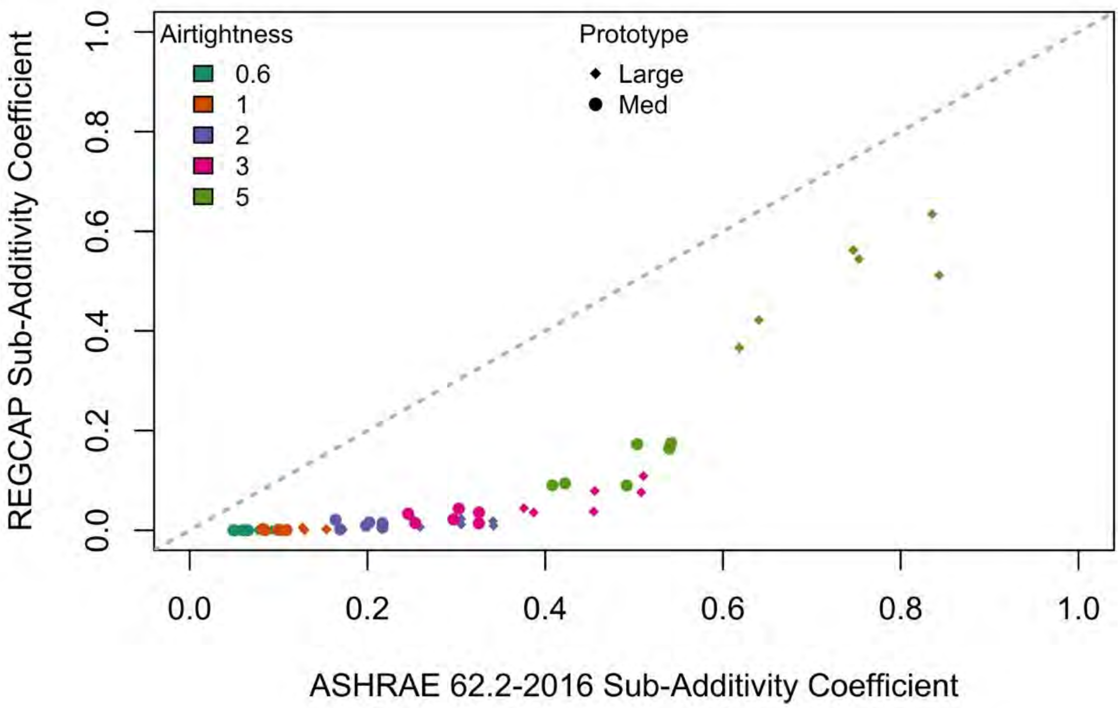
To assess this issue, we compared the sub-additivity coefficients (phi) from ASHRAE 62.2-2016 (based on the results in Hurel at al. (2016)) with those derived from the full mass-balance REGCAP model results from this study. The results are plotted in Figure 14 comparing the actual sub-additivity occurring in the REGCAP model mass balance with the estimates from the equations in ASHRAE 62.2-2016. For exhaust fans, less infiltration is contributed in the REGCAP model than is assumed by the standard for fan sizing. This was the case for all levels of airtightness and house prototypes. In fact, for most cases assessed, the sub-additivity coefficient was less than 0.1, which means that only 10% of the natural infiltration rate was added on top of the mechanical fan airflow. For many of the most airtight cases, the contribution was essentially zero. Values became clearly non-zero for the 3 and 5 ACH_{50} cases, though they are still well below the values assumed in the 62.2 fan sizing equations.

Hurel et al. (2016) reported that the sub-additivity model used in the standard is biased high at low infiltration rates (i.e., predicts more infiltration contribution than actually occurs), due to the use of the simple linear model in the ASHRAE standard, rather than the more accurate (though complicated) exponential model formulation (see Figure 5 in Hurel et al. for illustration of this bias). In addition, in Appendix E, Hurel et al. showed that relative to supply fans, exhaust fans had lower infiltration contributions. Exhaust fan sub-additivity predictions are expected to be biased low relative to the model used in 62.2, which was based on a mixture of exhaust and supply fans. Finally, Hurel et al.'s results show effectively zero infiltration contribution at 0.6 ACH_{50}, and they did not simulate any additional leakages between 0.6 and 3 ACH_{50}. HENGH simulations show near zero contributions for 0.6 and 1 ACH_{50} and very low contributions at 2 ACH_{50}. The sub-additivity behavior is clearly non-linear at very low leakage rates, and even the exponential model is at best an approximation of this.

For the simulations in this study, fan dominated airflow is occurring in the airtight exhaust fan cases. Essentially, no natural infiltration occurs whatsoever when the wind and stack pressures across leaks in the building envelope are less than the pressure induced by the exhaust fan, which can be very substantial in airtight homes. As a result, infiltration on top of fan airflow only occurs when it is particularly hot, cold or windy (or not at all in the 0.6 and 1 ACH_{50} cases). We have found similar results (i.e., infiltration is contributing much less than suggested by the ASHRAE standard) from the Title 24 leakage distribution in another study currently underway for the California Energy Commission that is using EnergyPlus and CONTAM in a co-simulation set-up.

Overall, these details support our finding that infiltration contributions are biased high in the ASHRAE 62.2-2016 sizing calculations relative to the HENGH REGCAP simulations. This results in under-sized Whole house fans, which is why our weighted average exposure was roughly 1.1 and not 1.0. Similarly, this very limited contribution of natural infiltration when combined with an exhaust fan explains why ventilation rates, exposures and energy usages were unchanging over the range from 0.6 to 3 ACH_{50} for exhaust fans sized using fixed airflow methods.

Figure 14 Comparison of sub-additivity coefficients between ASHRAE 62.2-2016 and REGCAP simulations.



An additional difference between the assumptions used to create the values of ϕ for ASHRAE 62.2 and the REGCAP calculations is in the envelope leakage distribution. The ASHRAE 62.2 approach is based on an average of one, two and three story homes where the fraction of leakage in the ceiling varies from 25% to 12.5% (Turner et al. (2012)). In the REGCAP simulations for this study we are using the leakage distribution assumptions of Title 24 with 50% of house leakage in the ceiling. These leakage distribution differences change both the estimates of infiltration and how unbalanced fans interact with building envelope lair flows (due to different natural infiltration pressures occurring across different parts of the building envelope). We re-ran a set of simulations using the leakage distributions reported in Table 16 for only 1-story homes using the 62.2-2016 fan sizing method. The sub-additivity coefficients we calculated for this new leakage distribution averaged 118% greater than those from the simulations using the Title 24 leakage distribution, but the new values were still 89% below the 62.2 model predictions (lower errors of 39% were found for the 5 ACH_{50} cases, as would be expected from the discussion above on the bias at low leakages). More details of these comparisons can be found together with additional discussion on differences between the weather files used to develop the ASHRAE 62.2 factors (TMY3) and the weather used in the current study (California Title 24-specific).

5 Discussion

In Section 5.1 through 5.7, we address the impacts of the simulation parameters that were varied, and through these discussions, we attempt to provide some guidance to the CEC in its specification of a Whole house fan sizing procedure and its option to include an airtightness requirement in the Title 24 code.

5.1 Prototype (1 story medium sized home and 2 story large home)

The differences in natural infiltration rates in 2- vs. 1-story homes had an important impact on energy and IAQ performance. The 2-story homes had substantial energy savings from airtightening, nearly double the savings in the 1-story homes, across all fan sizing methods. In fact, the 1-story homes sometimes increased energy consumption when airtightening and mechanically ventilating using the fan sizing methods in this work. Consistent with the energy savings in 2-story homes, these cases experienced the greatest changes in air exchange rates when air leakage was reduced, and their relative exposures increased as a result. After normalizing each case to have relative exposure equal to 1.0, the energy savings were very small for both 1 and 2 story prototype homes, though the two-story larger homes still had greater energy savings, by roughly a factor of two.

5.2 Fan Type (balanced or exhaust)

Fan type was a very important variable in this work. Overall, balanced fans had higher ventilation rates and energy consumption, with lower relative exposure and more variable exposure overall, because they do not interact in a sub-additive way with infiltration. These differences were much less pronounced for fan sizing methods that explicitly accounted for fan type (ASH622_2016 and T24_2019); these sizing methods were able to maintain reasonably consistent exposure near 1.0 across fan types, prototypes, climate zones, and airtightness.

It is prudent to leave fan type specification up to designers and builders. Yet, the code should not use fan calculation procedures that systematically worsen IAQ based on installed fan type. Comparing the current T24_2013 and the ASH622_2016 methods illustrates this well. The only difference between these sizing methods is that the ASH622_2016 requires larger exhaust fans due to their sub-additivity with infiltration. This results in weighted average exposure of 1.1 for ASH622_2016 vs. 1.31 for T24_2013. Failure to increase the required exhaust fan airflow due to sub-additivity worsens IAQ by 20% on average. In this context, it is notable that the adopted fan sizing method in the 2019 Title 24 includes a sub-addivity adjustment for unbalanced IAQ fans. This requirement will ensure there is no structural bias towards higher pollutant exposure in homes using unbalanced ventilation systems.

5.3 Climate Zone

Climate zones in California are generally mild, which limits the potential energy savings of reducing air leakage. Nevertheless, all climates in the state have varying temperature and wind driving forces that determine the natural infiltration rate of a home. As such, the fixed airflow fan sizing methods that did not adjust airflow based on estimated infiltration, and have fixed fan airflows across all climates, had widely varying relative exposures and air exchange rates. The fan sizing methods that account for infiltration in some way (ASH62.2_2016, T24_2019,, T24_2013) maintained much more consistent exposure and air exchange across climates. Energy savings from air leakage reduction were greatest in the coldest locations: CZ16 (Blue Canyon) and CZ1 (Arcata). When using an exhaust fan in a 1-story home sized to ASH62.2_2016, only CZ16 showed energy savings from reducing air leakage, while all other cases had unchanged or increased energy consumption.

5.4 Airtightness

Airtightness of the building envelope is of critical importance to the energy use and infiltration rates of a home. Yet, many of the fan sizing methods that we assessed ignored airtightness when designing the ventilation system (T24_2008, Qtotal, BuilderPractice, and to varying degrees, T24_2019). For these methods, a reduction in air leakage meant a reduction in house airflow and energy use, along with an increase in relative exposure and worsening IAQ. In these scenarios, reducing air leakage was shown to have consistent though modest whole house HVAC energy savings on the order of 4 to 5%, at the expense of higher pollutant exposure to occupants. In addition, these fan sizing methods were more likely to either under- or over-ventilate the homes relative to the target airflow, because they did not account for variable infiltration. For example, the 2019 adopted fan sizing method (T24_2019) tended to substantially over-ventilate all homes leakier than 2 ACH_{50} and to properly ventilate those below this level, due to use of the actual envelope leakage in fan sizing calculations. Other fan sizing methods explicitly accounted for infiltration, and adjusted fan airflows based on measured airtightness, climate zone and house type (ASH62.2_2016, T24_2013), and while still imperfect, these cases had more consistent ventilation rates, exposure and energy use across the parameters varied in our simulations.

When infiltration is accounted for in Whole house fan sizing, savings are roughly 1%, while fixed airflow sizing methods have 3 to 5% savings. This is because natural infiltration rates are low in California due to low driving forces, and for unbalanced fans, they interact non-linearly to further reduce air infiltration impacts on total airflow.

5.5 Fan Sizing Method

Ideally, a fan sizing method would ensure similar exposure and energy impacts across house types, fan types, airtightness and location. The ideal method would not predictably burden any homes in the state with either poor IAQ or artificially high energy use.

The first distinction between sizing methods is their treatment of infiltration. Fixed airflow methods do not account for infiltration at all, including T24_2008, Qtotal and BuilderPractice. These all have different fixed airflows, but they are similar in that they do not vary across any of our simulation parameters except house prototype. The adopted 2019 Title 24 sizing method accounts for infiltration driving forces as they vary by climate zone and house type (i.e., number of stories), but fails to account for critical differences in envelope leakage (e.g., 5 vs. 1 ACH_{50}), except for cases with leakage below 2 ACH_{50}. Finally, there are those sizing methods that attempt to account for all factors affecting infiltration rates—house leakage, climate zone and prototype—the current ASH62.2_2016 and the Total Ventilation Rate Method in the Title 24 (T24_2013).

Fan sizing methods also varied by their treatment of fan types, namely balanced vs. unbalanced fans. Nearly all methods treat the fan types as identical from an airflow calculation perspective, and as a result, the balanced fan cases tend to have higher overall airflow and energy use, along with lower exposure. Exhaust fans using these methods were shown to have higher exposure, due to their failure to account for sub-additivity with infiltration. It is notable that most new homes use simple exhaust ventilation systems to comply with Title 24 IAQ requirements. Some sizing methods (ASH62.2_2016 and T24_2019) include sub-additivity factors that effectively increase the required fan airflow if it is unbalanced, based on the magnitude of predicted infiltration relative to the target whole house airflow. These methods achieve more consistent whole house airflows and exposures across fan types.

The sizing methods with the poorest weighted average IAQ (highest exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24_2008) and the Total Ventilation Rate Method (T24_2013). These had weighted average relative exposure 30 and 40% worse than target levels, respectively. The only sizing method to maintain exposure below 1.0 in all cases was to simply size the Whole house fan to the whole house target airflow (Qtotal). The sizing method with weighted average exposure closest to 1.0 under current and future airtightness conditions was the adopted T24_2019 method. Current builder practice at current air tightness levels (about 5 ACH_{50}) has a mean relative exposure less than one and 3% less energy use than ASH622_2016 (and 10% less energy use when correct for equivalent exposure equal to one).

The ASH62.2_2016 sizing method accounts for all factors affecting infiltration and it adjusts airflow based on fan type. While imperfect, it achieves the greatest consistency across all our metrics of interest—ventilation airflow, energy use and relative exposure. Its weighted average exposure was 1.09, meaning it under-ventilated homes on average. The CEC could consider future development of customized sub-additivity coefficients for use in Title 24 fan sizing that would achieve average exposure very nearly equal to 1.0 in most cases. For example, an improvement would be to use the exponential sub-additivity model formulation described by Hurel et al., which mostly eliminates the bias in sub-additivity at low infiltration rates.

The adopted T24_2019 sizing method maintained weighted average relative exposure quite close to 1.0 under current air leakage and with a hypothetical 3 ACH_{50} leakage requirement in the energy code. Its weighted average energy use was higher than for the ASH622_2016 sizing method, but this was largely because exposure was lower with the T24_2019 method. In some cases this is desirable, but in the most common cases—with leakage of 3 and 5 ACH_{50}—the T24_2019 sizing method substantially over-ventilates the homes, with relative exposure in the range of 0.8 to 0.95, depending on the fan type and house prototype. The simplification of not requiring measured air leakage to be used in fan sizing leads to increased energy consumption in the most common homes with leaky envelopes. The median increases (across climate zones) in HVAC site energy use for the adopted T24_2019 relative to the ASH622_2016 method are shown by prototype, fan type and envelope leakage level in Table 12. Only 3 and 5 ACH_{50} cases are shown, as the fan sizing methods are identical for the 2, 1 and 0.6 ACH_{50} cases. The increased consumption for the T24_2019 method ranges from roughly 70 to 1,400 kWh/year. The energy differences are largest for the 5 ACH_{50}, which are the most over-ventilated relative to 62.2 targets. Balanced fans have larger energy penalties, as do the larger, 2-story prototype homes. On a weighted average basis, this incremental energy use for the T24_2019 sizing method was 241 kWh greater than for the ASH622_2016 sizing method.

Table 12 Median Increased HVAC Site Energy Use for T24_2019 vs. ASH622_2016, by Envelope Leakage, Prototype and Fan Type. Averaged across climate zones.

Envelope Leakage (ACH50)	Prototype	Fan Type	Increase HVAC Energy Use (kWh), T24_2019 vs. ASH622_2016
3	Large	B	573
3	Large	E	285
3	Med	B	222
3	Med	E	73
5	Large	B	1375
5	Large	E	677
5	Med	B	668
5	Med	E	337

5.6 Selecting a Fan Sizing Method and Considering an Airtightness Limit

We have shown that some energy savings are available through imposing an airtightness limit on new California homes, generally at the cost of worsened IAQ. The new construction-weighted average savings are modest—1 to 5% of annual HVAC consumption—and they depend on the fan sizing method used and other factors. Overall, only very modest savings are available (1%) from an airtightness limit, unless occupant pollutant exposure is also allowed to increase by 4-10% on a weighted average basis (i.e., higher in some cases and lower in others). Reducing air leakage can also be costly. In Table 13, we provide estimated costs for reducing leakage from 5 to 3 ACH_{50} for the two CEC prototype homes, based on estimates from the National Residential Efficiency Measures Database (NREL, n.d.). The Energy Commission will need to assess these potential energy savings in light of the costs and the statutory requirement for a negative declaration for measures in the building energy code.

Table 13 Estimated costs to seal the two CEC single-family prototype buildings from 5 to 3 ACH_{50}.

Prototype	Cost per ft^2 to Seal Home from 5 to 3 ACH_{50}		
	$0.22 (Low)	$0.52 (Average)	$0.82 (High)
1-story, 2,100 ft^2	$462	$1,092	$1,722
2-story, 2,700 ft^2	$594	$1,404	$2,214

There are three primary paths forward in terms of airtightness policy for new homes in the state: (1) Do nothing, (2) Impose a numeric air leakage limit for new homes (e.g., 3 ACH_{50}) and require blower door testing, or (3) Specify prescriptive measures designed to achieve increased airtightness and evaluate compliance via a checklist (or the like), similar to what has already been required in Section 110.7 of Title 24 since 2013. Each of these scenarios might lead to a different choice as to the most appropriate fan sizing method for the code. Overall, we recommend the CEC consider: (1) the consistency of the sizing method (i.e., its tendency to achieve similar whole house ventilation rates across houses and climates), and (2) the relative exposure currently and under an airtightness requirement in the code.

The adopted Title 24_2019 fan sizing method provides weighted average relative exposure very close to one under current air leakage weights, as well as under a hypothetical 3 ACH_{50} leakage limit in the energy code. This suggests that on average, the adopted fan sizing method is robust against policy decisions regarding air leakage requirements in new California homes. As noted elsewhere, the main downside of the adopted fan sizing method is its tendency to require over-sized IAQ fans in homes leakier than 2 ACH_{50}, with associated increased energy use. This bias towards over-ventilating leaky homes will reduce pollutant exposure in these cases, at the expense of increased energy use, which is consistent with the requirement of a negative declaration for Title 24 measures. An air leakage limit of 3 ACH_{50} would lead to a weighted average increase in exposure of 5% with the adopted fan sizing method, though the exposures are still below those maintained using the ASHRAE 62.2-2016 sizing method. This worsened IAQ would be greater in 2-story homes, averaging 8%, though again less than the exposure maintained in 2-story homes with fans sized to ASHRAE 62.2-2016. If an air leakage limit were imposed while using the adopted fan sizing method, weighted average site energy savings would be 3.6% (252 kWh/year). Savings would be greater in 2-story, larger homes, at 5.2% vs. 1.3% in 1-story.

If the energy savings are normalized so that all approaches have relative exposure of one then the savings of tightening from 5 ACH_{50} to 3 ACH_{50} are all reduced because the savings are at the expense of increased exposure. The resulting energy savings are less than 200 kWh/year except for CZ16 where savings are about 500 kWh/yr (about 5% of total HVAC energy use).

5.7 Additional Considerations

There are some additional considerations not included directly in this work, but that the CEC might consider in selecting a fan sizing method, and in deciding whether or not to impose airtightness requirements.

Before imposing air tightness limits, we need to consider that the companion field study (Chan et al. 2018) found that like Whole house fans used for Title 24 compliance are turned off permanently in about three quarters of new California homes (similar results have been found in other parts of the country (Sonne, Withers, & Vieira, 2015). While technically out of control of code officials, the decision of whether or not to impose an air leakage limit in new homes should include consideration of this very real phenomenon. Under an airtightness limit, the impacts on human health of having the Whole house fan turned off worsen. Our weighted average results show that these homes would increase their relative exposure by a factor of roughly 1.5, to over 4 times the target exposure for new homes with Whole house fans operating continuously. The CEC should consider additional safeguards and/or homeowner education requirements that encourage occupants to keep their fans turned on. Labeling of fan control switches, elimination of occupant-controlled switches, further reductions in minimum noise-level requirements, etc. are all options that might ensure that more fans are operated as intended.

Second, is that installed ventilation airflows commonly exceed the code-minimum specification, by about 40-50%. Data from the companion field study indicate that this is likely due to limited fan airflow options on the market. The proposed fan sizing methods under serious consideration here (i.e., ASH62.2_2016 and T24_2019), substantially increase the minimum airflows required to satisfy Title 24 relative to the current prescriptive fans sized using the Fan Ventilation Rate method (T24_2008), and align within a few cfm of current builder practice. The state should consider available options to ensure that installed fan airflows are either aligned with the calculated values in the code (modulating fans that are set by installers or use of timers), or demonstration of compliance should include these increased airflows, such that other efficiency measures are used to offset increased ventilation energy.

6 Conclusions

Energy, ventilation and IAQ performance were simulated in two prototype homes compliant with the 2016 prescriptive provisions of Title 24, across a number of California climate zones (CZ 1, 3, 10, 12, 13 and 16) reflecting the variety of climate conditions in the state. Airtightness was varied between 0.6 and 5 ACH_{50}, and Whole house fans were sized according to six currently available or proposed compliance paths in Title 24 or ASHRAE Standard 62.2. Fan sizing methods either accounted for infiltration and fan type, or they used a fixed airflow approach, with no variability in the fan sizing by airtightness, climate zones, geometry and fan types. The objectives of this work were to: (1) evaluate the IAQ and energy impacts of different Whole house fan sizing methods, and (2) to assess the impacts of a hypothetical 3 ACH_{50} airtightness requirement in the Title 24 energy code.

None of the fan sizing methods were perfect, despite the efforts made in some cases to account for all the major factors affecting house air exchange (e.g., house geometery, airtightness, fan type, location). The sizing methods with the poorest weighted average IAQ (highest exposure) were those currently in Title 24 as compliance paths—the Fan Ventilation Rate Method (T24_2008) and the Total Ventilation Rate Method (T24_2013). These had weighted average relative exposures 30 and 40% worse than target levels, respectively. Of all sizing methods, the adopted Title 24 2019 sizing method with a sub-additivity adjustement for unbalanced fans (T24_2019) maintained relative exposure closest to 1.0 under both current and future airtightness weightings (with exposures of 0.97 and 1.02, respectively). The two closest competitors were the current ASHRAE 62.2-2016 method (ASH622_2016) and the Qtotal method that sizes the fan to the total target ventilation rate in the ASHRAE standard. The ASH622_2016 method was consistently under-ventilated (at 1.09 and 1.06 under current and future airtightness weights), while the Qtotal method was consistently over-ventilated (at 0.93 and 0.97). Qtotal was the only sizing method that maintained exposure below 1.0 in all simulated cases. Under current airtightness weights, the T24_2019 and Qtotal methods increased weighted average energy use by 3 and 5% relative to the ASH622_2016 method (and by 1 and 3% under future airtightness weights). The difference in weighted average total consumption between any of these three sizing methods was roughly 300 kWh/year (these absolute differences were greater in harsher climate zones)

When all cases are examined individually, most of the sizing methods had widely spread relative exposure values, meaning that most homes were either substantially under- or over-ventilated relative to target rates in 62.2 and Title 24. This inconsistency increases the risk of either poor IAQ or excess energy consumption for individual homes, even when the weighted average results are acceptable (as they were for the T24_2019 method, for example). Exposure was generally higher in more airtight homes, in homes with exhaust fans, and in 1-story homes. The ASHRAE 62.2-2016 fan sizing method, which accounts fully for infiltration and fan type, had the most consistent pollutant exposure and ventilation rates across all cases, irrespective of climate zone, fan type, airtightness or house prototype. This sizing method had average exposure of 1.09, due to biases in the exhaust fan sub-additivity calculations in ASHRAE 62.2-2016. If desired, the CEC could adopt an alternative sub-additivity formulation that would eliminate most of this bias, and should reduce average exposure very close to 1.0. The adopted Title 24_2019 fan sizing method also had quite consistent exposure values, though it tended to over-ventilate leakier homes. Unlike the ASHRAE 62.2-2016 method, other sizing methods had drastically different performance for balanced vs. exhaust fans, as well as at differing airtightness levels and climate zones.

An airtightness requirement of 3 ACH_{50} in new California homes was found to have marginal predicted weighted average energy savings (1 to 5% of total HVAC) when also providing continuous mechanical ventilation. Most of these savings were from reducing the ventilation rate and worsening IAQ. The fixed airflow fan sizing methods saved more energy (roughly 3 to 5%) but worsened IAQ (increased exposure by 5 to 24%). Energy use increased as weighted average exposure was reduced, essentially trading off poor IAQ for improved energy performance. If the changes in exposure are accounted for by normalizing to the same exposure, these energy savings are substantially reduced to typically less than 1% savings apart from CZ16 where savings are about 5%. The sizing methods that accounted for infiltration and/or fan type had substantially reduced weighted average energy savings (1%), while they marginally improved IAQ (reduced exposure by roughly 3 to 4%) under an airtightness requirement. In fact, for the ASH622_2016 sizing method, energy use increased under an airtightness regime for 1-story homes with exhaust fans in all climate zones except CZ16. Airtightness savings were roughly double in the 2-story vs. 1-story prototype homes, because of their increased natural infiltration rates (due to greater building height). Savings were also higher in select climates with the harshest weather (e.g., CZ16 in Blue Canyon and CZ1 Arcata), but the lack of new construction in these zones nearly eliminated their effect on the weighted average results. The estimated costs for air sealing from 5 to 3 ACH_{50} averaged $1,092 and $1,404 for the 1- and 2-story prototypes, respectively.

The adopted fan sizing method in the 2019 Title 24 energy code is fairly robust against policy decisions regarding air leakage limits in the energy code, as it provided weighted average exposure nearly equal to 1 under both airtightness scenarios (existing and airtightened). Weighted average exposure would increase 5% with an air leakage limit in the energy code, though it would still be less than exposure achieved using the ASH622_2016 sizing method. Our results suggest that unless occupant pollutant exposure is allowed to increase by 5-10% relative to target rates, then an airtightness limit will have very marginal savings of roughly 1% of annual HVAC energy. If exposure is allowed to increase, then savings of 3-5% are possible through airtightening. Consistent with this, when all cases were normalized to have the same IAQ, the HVAC energy savings from an airtightness limit in the code were reduced to well below 1%.

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Appendix B-1

Simulation Data Tables

Table 14 Tabular summary of HVAC energy end-uses, air exchange rate, Whole house fan airflow and relative exposure for all cases.

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	0.6	T24_2008	B	1	64	166	7237	0	230	7633	9243	0.179	1.521
Large	0.6	T24_2008	B	3	64	282	3300	1110	230	4921	5704	0.176	1.550
Large	0.6	T24_2008	B	10	64	577	1491	2973	230	5271	5839	0.171	1.599
Large	0.6	T24_2008	B	12	64	583	4477	2603	230	7892	8865	0.175	1.555
Large	0.6	T24_2008	B	13	64	746	4519	3489	230	8984	10099	0.171	1.592
Large	0.6	T24_2008	B	16	64	523	10053	1515	230	12320	14246	0.180	1.522
Large	0.6	T24_2008	E	1	64	154	6700	0	115	6968	8991	0.148	1.833
Large	0.6	T24_2008	E	3	64	286	3084	1157	115	4642	5597	0.148	1.834
Large	0.6	T24_2008	E	10	64	577	1321	2988	115	5001	5566	0.148	1.832
Large	0.6	T24_2008	E	12	64	576	4109	2608	115	7408	8466	0.148	1.833
Large	0.6	T24_2008	E	13	64	737	4161	3480	115	8492	9652	0.148	1.834
Large	0.6	T24_2008	E	16	64	505	9146	1534	115	11300	13526	0.148	1.834
Large	0.6	T24_2013	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	T24_2013	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	T24_2013	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	T24_2013	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	T24_2013	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	T24_2013	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	T24_2013	E	1	107	191	8345	0	193	8729	9120	0.249	1.094
Large	0.6	T24_2013	E	3	107	285	3950	1051	193	5480	5658	0.250	1.090
Large	0.6	T24_2013	E	10	109	572	1827	2927	197	5523	5605	0.255	1.068
Large	0.6	T24_2013	E	12	108	583	5037	2549	194	8364	8552	0.251	1.084
Large	0.6	T24_2013	E	13	109	751	5047	3471	196	9465	9640	0.253	1.074
Large	0.6	T24_2013	E	16	109	530	10948	1441	196	13116	13439	0.254	1.072
Large	0.6	Qtotal	B	1	117	216	9439	0	421	10076	9482	0.305	0.893
Large	0.6	Qtotal	B	3	117	281	4467	965	421	6134	5880	0.301	0.904

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	0.6	Qtotal	B	10	117	576	2187	2907	421	6090	5952	0.296	0.922
Large	0.6	Qtotal	B	12	117	596	5714	2539	421	9271	8975	0.301	0.906
Large	0.6	Qtotal	B	13	117	768	5668	3493	421	10351	10088	0.296	0.919
Large	0.6	Qtotal	B	16	117	559	12434	1414	421	14827	14153	0.306	0.891
Large	0.6	Qtotal	E	1	117	201	8748	0	211	9159	9159	0.272	1.000
Large	0.6	Qtotal	E	3	117	286	4152	1029	211	5677	5677	0.272	1.000
Large	0.6	Qtotal	E	10	117	571	1912	2916	211	5611	5611	0.272	1.000
Large	0.6	Qtotal	E	12	117	585	5224	2537	211	8557	8557	0.272	1.000
Large	0.6	Qtotal	E	13	117	754	5193	3470	211	9627	9627	0.272	1.000
Large	0.6	Qtotal	E	16	117	535	11287	1427	211	13459	13459	0.272	1.000
Large	0.6	ASH62.2_2016	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	ASH62.2_2016	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	ASH62.2_2016	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	ASH62.2_2016	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	ASH62.2_2016	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	ASH62.2_2016	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	ASH62.2_2016	E	1	116	200	8716	0	209	9125	9159	0.270	1.007
Large	0.6	ASH62.2_2016	E	3	116	286	4137	1031	209	5663	5678	0.270	1.007
Large	0.6	ASH62.2_2016	E	10	116	572	1908	2918	210	5607	5612	0.271	1.004
Large	0.6	ASH62.2_2016	E	12	116	585	5212	2537	209	8544	8559	0.271	1.006
Large	0.6	ASH62.2_2016	E	13	116	753	5183	3470	210	9615	9627	0.271	1.005
Large	0.6	ASH62.2_2016	E	16	116	534	11264	1428	210	13437	13458	0.271	1.005
Large	0.6	T24_2019	B	1	107	207	9023	0	385	9615	9451	0.281	0.968
Large	0.6	T24_2019	B	3	107	280	4229	990	386	5886	5833	0.279	0.978
Large	0.6	T24_2019	B	10	109	575	2070	2916	394	5955	5923	0.278	0.980
Large	0.6	T24_2019	B	12	108	594	5507	2551	388	9041	8969	0.279	0.975
Large	0.6	T24_2019	B	13	109	765	5480	3494	392	10131	10076	0.277	0.982
Large	0.6	T24_2019	B	16	109	552	12059	1427	393	14432	14137	0.287	0.949
Large	0.6	T24_2019	E	1	116	200	8716	0	209	9125	9159	0.270	1.007
Large	0.6	T24_2019	E	3	116	286	4137	1031	209	5663	5678	0.270	1.007
Large	0.6	T24_2019	E	10	116	572	1908	2918	210	5607	5612	0.271	1.004

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	0.6	T24_2019	E	12	116	585	5212	2537	209	8544	8559	0.271	1.006
Large	0.6	T24_2019	E	13	116	753	5183	3470	210	9615	9627	0.271	1.005
Large	0.6	T24_2019	E	16	116	534	11264	1428	210	13437	13458	0.271	1.005
Large	0.6	BuilderPractice	B	1	89	190	8277	0	321	8789	9372	0.239	1.137
Large	0.6	BuilderPractice	B	3	89	280	3830	1039	321	5471	5776	0.236	1.154
Large	0.6	BuilderPractice	B	10	89	576	1821	2942	321	5660	5904	0.231	1.182
Large	0.6	BuilderPractice	B	12	89	589	5073	2573	321	8556	8937	0.236	1.157
Large	0.6	BuilderPractice	B	13	89	756	5055	3492	321	9625	10076	0.231	1.179
Large	0.6	BuilderPractice	B	16	89	538	11120	1464	321	13442	14098	0.240	1.136
Large	0.6	BuilderPractice	E	1	89	175	7643	0	161	7979	9046	0.208	1.310
Large	0.6	BuilderPractice	E	3	89	285	3577	1094	161	5117	5620	0.208	1.310
Large	0.6	BuilderPractice	E	10	89	574	1590	2955	161	5279	5576	0.208	1.310
Large	0.6	BuilderPractice	E	12	89	580	4647	2575	161	7963	8529	0.208	1.310
Large	0.6	BuilderPractice	E	13	89	745	4671	3474	161	9051	9656	0.208	1.311
Large	0.6	BuilderPractice	E	16	89	518	10115	1480	161	12273	13404	0.208	1.310
Large	0.6	None	B	1	0	111	4848	0	0	4959	8638	0.028	9.815
Large	0.6	None	B	3	0	290	2071	1296	0	3657	5259	0.025	10.922
Large	0.6	None	B	10	0	572	827	2977	0	4376	5097	0.021	14.317
Large	0.6	None	B	12	0	561	3177	2613	0	6351	8539	0.025	11.348
Large	0.6	None	B	13	0	705	3202	3389	0	7296	9792	0.021	13.895
Large	0.6	None	B	16	0	483	7093	1682	0	9259	15546	0.028	10.998
Large	0.6	None	E	1	0	111	4848	0	0	4959	8638	0.028	9.815
Large	0.6	None	E	3	0	290	2071	1296	0	3657	5259	0.025	10.922
Large	0.6	None	E	10	0	572	827	2977	0	4376	5097	0.021	14.317
Large	0.6	None	E	12	0	561	3177	2613	0	6351	8539	0.025	11.348
Large	0.6	None	E	13	0	705	3202	3389	0	7296	9792	0.021	13.895
Large	0.6	None	E	16	0	483	7093	1682	0	9259	15546	0.028	10.998
Large	1	T24_2008	B	1	64	173	7527	0	230	7930	9229	0.197	1.384
Large	1	T24_2008	B	3	64	282	3451	1092	230	5054	5709	0.192	1.421
Large	1	T24_2008	B	10	64	576	1584	2961	230	5351	5853	0.184	1.487
Large	1	T24_2008	B	12	64	584	4660	2591	230	8065	8886	0.192	1.426

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	1	T24_2008	B	13	64	748	4666	3483	230	9127	10092	0.185	1.477
Large	1	T24_2008	B	16	64	531	10503	1503	230	12766	14371	0.198	1.388
Large	1	T24_2008	E	1	64	154	6727	0	115	6996	9026	0.149	1.827
Large	1	T24_2008	E	3	64	285	3091	1154	115	4645	5599	0.149	1.830
Large	1	T24_2008	E	10	64	576	1334	2985	115	5010	5579	0.149	1.827
Large	1	T24_2008	E	12	64	576	4135	2605	115	7431	8498	0.149	1.826
Large	1	T24_2008	E	13	64	737	4182	3477	115	8511	9684	0.148	1.833
Large	1	T24_2008	E	16	64	507	9218	1533	115	11372	13652	0.149	1.831
Large	1	T24_2013	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	T24_2013	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	T24_2013	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	T24_2013	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	T24_2013	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	T24_2013	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	T24_2013	E	1	100	186	8111	0	181	8477	9129	0.234	1.165
Large	1	T24_2013	E	3	101	285	3817	1064	182	5348	5642	0.235	1.159
Large	1	T24_2013	E	10	104	572	1783	2930	188	5473	5609	0.243	1.118
Large	1	T24_2013	E	12	102	583	4936	2555	183	8257	8571	0.237	1.148
Large	1	T24_2013	E	13	103	750	4962	3470	186	9368	9661	0.241	1.129
Large	1	T24_2013	E	16	104	527	10776	1451	187	12941	13483	0.242	1.126
Large	1	Qtotal	B	1	117	224	9758	0	421	10403	9489	0.323	0.844
Large	1	Qtotal	B	3	117	281	4624	948	421	6275	5882	0.317	0.859
Large	1	Qtotal	B	10	117	576	2278	2898	421	6173	5957	0.309	0.884
Large	1	Qtotal	B	12	117	598	5891	2528	421	9438	8978	0.317	0.861
Large	1	Qtotal	B	13	117	771	5830	3489	421	10511	10101	0.310	0.880
Large	1	Qtotal	B	16	117	567	12885	1405	421	15278	14236	0.324	0.843
Large	1	Qtotal	E	1	117	201	8767	0	211	9179	9177	0.272	1.000
Large	1	Qtotal	E	3	117	285	4157	1027	211	5680	5679	0.272	1.000
Large	1	Qtotal	E	10	117	571	1923	2914	211	5619	5618	0.272	0.999
Large	1	Qtotal	E	12	117	585	5245	2535	211	8575	8575	0.272	1.000
Large	1	Qtotal	E	13	117	754	5222	3468	211	9654	9654	0.272	1.000

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	1	Qtotal	E	16	117	536	11333	1427	211	13506	13505	0.272	1.000
Large	1	ASH62.2_2016	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	ASH62.2_2016	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	ASH62.2_2016	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	ASH62.2_2016	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	ASH62.2_2016	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	ASH62.2_2016	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	ASH62.2_2016	E	1	114	199	8678	0	206	9083	9176	0.267	1.020
Large	1	ASH62.2_2016	E	3	115	285	4110	1032	207	5634	5674	0.267	1.019
Large	1	ASH62.2_2016	E	10	115	571	1911	2916	208	5606	5620	0.269	1.011
Large	1	ASH62.2_2016	E	12	115	585	5204	2537	207	8533	8573	0.268	1.017
Large	1	ASH62.2_2016	E	13	115	753	5180	3468	208	9609	9642	0.269	1.013
Large	1	ASH62.2_2016	E	16	115	535	11270	1429	208	13442	13502	0.269	1.013
Large	1	T24_2019	B	1	100	208	9059	0	361	9627	9431	0.284	0.961
Large	1	T24_2019	B	3	101	281	4246	990	363	5880	5821	0.279	0.975
Large	1	T24_2019	B	10	104	575	2099	2909	376	5959	5921	0.279	0.977
Large	1	T24_2019	B	12	102	594	5543	2546	366	9049	8963	0.281	0.970
Large	1	T24_2019	B	13	103	765	5519	3488	373	10144	10082	0.279	0.979
Large	1	T24_2019	B	16	104	557	12260	1427	374	14618	14219	0.293	0.933
Large	1	T24_2019	E	1	114	199	8678	0	206	9083	9176	0.267	1.020
Large	1	T24_2019	E	3	115	285	4110	1032	207	5634	5674	0.267	1.019
Large	1	T24_2019	E	10	115	571	1911	2916	208	5606	5620	0.269	1.011
Large	1	T24_2019	E	12	115	585	5204	2537	207	8533	8573	0.268	1.017
Large	1	T24_2019	E	13	115	753	5180	3468	208	9609	9642	0.269	1.013
Large	1	T24_2019	E	16	115	535	11270	1429	208	13442	13502	0.269	1.013
Large	1	BuilderPractice	B	1	89	197	8580	0	321	9099	9368	0.257	1.059
Large	1	BuilderPractice	B	3	89	280	3971	1022	321	5595	5766	0.252	1.082
Large	1	BuilderPractice	B	10	89	575	1910	2928	321	5735	5905	0.244	1.120
Large	1	BuilderPractice	B	12	89	591	5252	2561	321	8726	8944	0.252	1.085
Large	1	BuilderPractice	B	13	89	758	5200	3488	321	9768	10073	0.245	1.114
Large	1	BuilderPractice	B	16	89	546	11572	1454	321	13893	14207	0.258	1.060

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	1	BuilderPractice	E	1	89	176	7671	0	161	8008	9079	0.208	1.309
Large	1	BuilderPractice	E	3	89	285	3582	1091	161	5118	5620	0.208	1.309
Large	1	BuilderPractice	E	10	89	573	1601	2952	161	5286	5583	0.208	1.308
Large	1	BuilderPractice	E	12	89	580	4669	2572	161	7983	8552	0.208	1.309
Large	1	BuilderPractice	E	13	89	745	4691	3472	161	9068	9679	0.208	1.310
Large	1	BuilderPractice	E	16	89	519	10172	1479	161	12331	13477	0.208	1.310
Large	1	None	B	1	0	117	5121	0	0	5238	8683	0.047	5.945
Large	1	None	B	3	0	288	2211	1273	0	3772	5324	0.042	6.610
Large	1	None	B	10	0	570	901	2956	0	4426	5224	0.035	8.677
Large	1	None	B	12	0	561	3340	2598	0	6499	8620	0.042	6.895
Large	1	None	B	13	0	706	3370	3377	0	7453	10057	0.035	8.408
Large	1	None	B	16	0	490	7530	1658	0	9678	15645	0.047	6.695
Large	1	None	E	1	0	117	5121	0	0	5238	8683	0.047	5.945
Large	1	None	E	3	0	288	2211	1273	0	3772	5324	0.042	6.610
Large	1	None	E	10	0	570	901	2956	0	4426	5224	0.035	8.677
Large	1	None	E	12	0	561	3340	2598	0	6499	8620	0.042	6.895
Large	1	None	E	13	0	706	3370	3377	0	7453	10057	0.035	8.408
Large	1	None	E	16	0	490	7530	1658	0	9678	15645	0.047	6.695
Large	2	T24_2008	B	1	64	191	8333	0	230	8754	9308	0.242	1.132
Large	2	T24_2008	B	3	64	282	3834	1046	230	5391	5730	0.232	1.179
Large	2	T24_2008	B	10	64	575	1820	2928	230	5552	5886	0.217	1.272
Large	2	T24_2008	B	12	64	588	5108	2562	230	8488	8925	0.232	1.186
Large	2	T24_2008	B	13	64	753	5048	3471	230	9502	10111	0.220	1.254
Large	2	T24_2008	B	16	64	551	11600	1476	230	13857	14607	0.243	1.144
Large	2	T24_2008	E	1	64	158	6906	0	115	7179	9174	0.156	1.757
Large	2	T24_2008	E	3	64	284	3137	1141	115	4678	5622	0.152	1.799
Large	2	T24_2008	E	10	64	575	1405	2967	115	5061	5646	0.153	1.791
Large	2	T24_2008	E	12	64	577	4288	2592	115	7572	8649	0.156	1.752
Large	2	T24_2008	E	13	64	738	4311	3470	115	8634	9843	0.152	1.790
Large	2	T24_2008	E	16	64	522	9906	1528	115	12070	14470	0.162	1.698
Large	2	T24_2013	B	1	83	210	9169	0	301	9680	9409	0.289	0.947

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	2	T24_2013	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	T24_2013	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	T24_2013	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	T24_2013	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	T24_2013	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	T24_2013	E	1	83	173	7547	0	151	7870	9141	0.197	1.382
Large	2	T24_2013	E	3	85	284	3521	1093	153	5051	5625	0.199	1.369
Large	2	T24_2013	E	10	92	572	1689	2936	166	5362	5636	0.216	1.263
Large	2	T24_2013	E	12	86	580	4705	2566	156	8007	8627	0.205	1.332
Large	2	T24_2013	E	13	90	746	4774	3466	162	9148	9744	0.211	1.291
Large	2	T24_2013	E	16	91	526	10511	1473	163	12673	13789	0.214	1.276
Large	2	Qtotal	B	1	117	243	10588	0	421	11252	9534	0.367	0.744
Large	2	Qtotal	B	3	117	283	5013	908	421	6624	5890	0.357	0.765
Large	2	Qtotal	B	10	117	575	2504	2867	421	6367	5965	0.341	0.803
Large	2	Qtotal	B	12	117	602	6332	2498	421	9854	8988	0.357	0.767
Large	2	Qtotal	B	13	117	777	6236	3476	421	10910	10132	0.344	0.796
Large	2	Qtotal	B	16	117	590	14034	1384	421	16428	14443	0.369	0.745
Large	2	Qtotal	E	1	117	203	8847	0	211	9261	9237	0.274	0.995
Large	2	Qtotal	E	3	117	285	4187	1019	211	5701	5695	0.273	0.997
Large	2	Qtotal	E	10	117	570	1963	2903	211	5646	5640	0.274	0.996
Large	2	Qtotal	E	12	117	585	5318	2526	211	8640	8626	0.274	0.994
Large	2	Qtotal	E	13	117	754	5279	3462	211	9706	9703	0.273	0.999
Large	2	Qtotal	E	16	117	539	11509	1424	211	13683	13671	0.273	0.998
Large	2	ASH62.2_2016	B	1	83	210	9169	0	301	9680	9409	0.289	0.947
Large	2	ASH62.2_2016	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	ASH62.2_2016	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	ASH62.2_2016	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	ASH62.2_2016	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	ASH62.2_2016	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	ASH62.2_2016	E	1	107	194	8459	0	193	8846	9197	0.252	1.082
Large	2	ASH62.2_2016	E	3	108	284	3994	1039	195	5511	5669	0.253	1.078

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	2	ASH62.2_2016	E	10	111	571	1907	2910	201	5589	5643	0.261	1.043
Large	2	ASH62.2_2016	E	12	109	584	5162	2537	196	8479	8630	0.256	1.065
Large	2	ASH62.2_2016	E	13	111	752	5156	3463	200	9571	9703	0.258	1.054
Large	2	ASH62.2_2016	E	16	111	536	11271	1435	200	13442	13681	0.259	1.050
Large	2	T24_2019	B	1	83	210	9169	0	301	9680	9409	0.289	0.947
Large	2	T24_2019	B	3	85	282	4296	990	305	5873	5805	0.281	0.971
Large	2	T24_2019	B	10	92	575	2180	2896	331	5982	5934	0.283	0.971
Large	2	T24_2019	B	12	86	594	5641	2535	312	9083	8967	0.286	0.961
Large	2	T24_2019	B	13	90	765	5628	3475	325	10192	10115	0.281	0.975
Large	2	T24_2019	B	16	91	569	12774	1427	327	15096	14444	0.307	0.899
Large	2	T24_2019	E	1	107	194	8459	0	193	8846	9197	0.252	1.082
Large	2	T24_2019	E	3	108	284	3994	1039	195	5511	5669	0.253	1.078
Large	2	T24_2019	E	10	111	571	1907	2910	201	5589	5643	0.261	1.043
Large	2	T24_2019	E	12	109	584	5162	2537	196	8479	8630	0.256	1.065
Large	2	T24_2019	E	13	111	752	5156	3463	200	9571	9703	0.258	1.054
Large	2	T24_2019	E	16	111	536	11271	1435	200	13442	13681	0.259	1.050
Large	2	BuilderPractice	B	1	89	216	9399	0	321	9935	9426	0.302	0.906
Large	2	BuilderPractice	B	3	89	282	4404	978	321	5986	5828	0.292	0.936
Large	2	BuilderPractice	B	10	89	575	2147	2899	321	5943	5933	0.277	0.994
Large	2	BuilderPractice	B	12	89	595	5702	2532	321	9151	8970	0.292	0.940
Large	2	BuilderPractice	B	13	89	764	5606	3475	321	10166	10113	0.279	0.983
Large	2	BuilderPractice	B	16	89	568	12702	1429	321	15021	14446	0.304	0.910
Large	2	BuilderPractice	E	1	89	178	7765	0	161	8104	9163	0.210	1.297
Large	2	BuilderPractice	E	3	89	283	3607	1082	161	5134	5629	0.209	1.303
Large	2	BuilderPractice	E	10	89	572	1663	2939	161	5335	5639	0.210	1.300
Large	2	BuilderPractice	E	12	89	580	4755	2563	161	8059	8623	0.211	1.294
Large	2	BuilderPractice	E	13	89	745	4759	3466	161	9132	9750	0.209	1.305
Large	2	BuilderPractice	E	16	89	525	10460	1476	161	12621	13803	0.210	1.296
Large	2	None	B	1	0	134	5826	0	0	5959	8824	0.093	3.021
Large	2	None	B	3	0	287	2564	1223	0	4075	5439	0.083	3.356
Large	2	None	B	10	0	578	1062	2984	0	4624	5653	0.069	4.399

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	2	None	B	12	0	563	3749	2566	0	6878	8738	0.083	3.519
Large	2	None	B	13	0	727	3695	3448	0	7871	10332	0.071	4.200
Large	2	None	B	16	0	509	8653	1615	0	10777	15966	0.093	3.416
Large	2	None	E	1	0	134	5826	0	0	5959	8824	0.093	3.021
Large	2	None	E	3	0	287	2564	1223	0	4075	5439	0.083	3.356
Large	2	None	E	10	0	578	1062	2984	0	4624	5653	0.069	4.399
Large	2	None	E	12	0	563	3749	2566	0	6878	8738	0.083	3.519
Large	2	None	E	13	0	727	3695	3448	0	7871	10332	0.071	4.200
Large	2	None	E	16	0	509	8653	1615	0	10777	15966	0.093	3.416
Large	3	T24_2008	B	1	64	210	9150	0	230	9590	9387	0.287	0.960
Large	3	T24_2008	B	3	64	283	4216	1004	230	5732	5755	0.272	1.010
Large	3	T24_2008	B	10	64	573	2036	2899	230	5737	5902	0.250	1.116
Large	3	T24_2008	B	12	64	593	5563	2533	230	8918	8972	0.273	1.019
Large	3	T24_2008	B	13	64	759	5443	3459	230	9891	10151	0.254	1.094
Large	3	T24_2008	B	16	64	571	12678	1451	230	14929	14785	0.288	0.977
Large	3	T24_2008	E	1	64	174	7568	0	115	7857	9319	0.193	1.441
Large	3	T24_2008	E	3	64	284	3427	1107	115	4933	5713	0.179	1.543
Large	3	T24_2008	E	10	64	573	1601	2935	115	5224	5774	0.173	1.610
Large	3	T24_2008	E	12	64	581	4726	2565	115	7986	8882	0.187	1.485
Large	3	T24_2008	E	13	64	744	4685	3454	115	8997	10075	0.175	1.569
Large	3	T24_2008	E	16	64	545	11043	1511	115	13214	15136	0.201	1.419
Large	3	T24_2013	B	1	67	213	9286	0	241	9740	9403	0.294	0.935
Large	3	T24_2013	B	3	69	283	4336	991	247	5857	5783	0.283	0.969
Large	3	T24_2013	B	10	79	575	2249	2883	286	5993	5941	0.287	0.969
Large	3	T24_2013	B	12	71	595	5739	2524	257	9116	8980	0.291	0.954
Large	3	T24_2013	B	13	77	765	5746	3461	276	10248	10165	0.284	0.973
Large	3	T24_2013	B	16	78	580	13284	1426	280	15570	14679	0.321	0.872
Large	3	T24_2013	E	1	67	175	7626	0	121	7921	9342	0.195	1.420
Large	3	T24_2013	E	3	69	284	3462	1102	124	4972	5711	0.183	1.501
Large	3	T24_2013	E	10	79	572	1697	2928	143	5341	5741	0.198	1.393
Large	3	T24_2013	E	12	71	582	4795	2559	129	8065	8853	0.196	1.409

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	3	T24_2013	E	13	77	745	4798	3457	138	9139	9973	0.194	1.409
Large	3	T24_2013	E	16	78	545	11205	1490	140	13380	14736	0.218	1.286
Large	3	Qtotal	B	1	117	262	11442	0	421	12125	9593	0.411	0.666
Large	3	Qtotal	B	3	117	285	5422	868	421	6995	5915	0.396	0.691
Large	3	Qtotal	B	10	117	576	2770	2842	421	6609	6010	0.374	0.738
Large	3	Qtotal	B	12	117	607	6775	2471	421	10274	9006	0.397	0.693
Large	3	Qtotal	B	13	117	783	6648	3465	421	11317	10169	0.378	0.728
Large	3	Qtotal	B	16	117	612	15152	1363	421	17547	14603	0.414	0.670
Large	3	Qtotal	E	1	117	206	8980	0	211	9397	9324	0.277	0.985
Large	3	Qtotal	E	3	117	284	4241	1009	211	5745	5725	0.275	0.991
Large	3	Qtotal	E	10	117	570	2029	2890	211	5700	5686	0.276	0.990
Large	3	Qtotal	E	12	117	586	5435	2516	211	8747	8698	0.278	0.981
Large	3	Qtotal	E	13	117	755	5376	3456	211	9798	9777	0.274	0.992
Large	3	Qtotal	E	16	117	551	12043	1421	211	14226	14077	0.281	0.973
Large	3	ASH62.2_2016	B	1	67	213	9286	0	241	9740	9403	0.294	0.935
Large	3	ASH62.2_2016	B	3	69	283	4336	991	247	5857	5783	0.283	0.969
Large	3	ASH62.2_2016	B	10	79	575	2249	2883	286	5993	5941	0.287	0.969
Large	3	ASH62.2_2016	B	12	71	595	5739	2524	257	9116	8980	0.291	0.954
Large	3	ASH62.2_2016	B	13	77	765	5746	3461	276	10248	10165	0.284	0.973
Large	3	ASH62.2_2016	B	16	78	580	13284	1426	280	15570	14679	0.321	0.872
Large	3	ASH62.2_2016	E	1	95	189	8244	0	172	8605	9317	0.233	1.175
Large	3	ASH62.2_2016	E	3	97	283	3846	1052	175	5356	5698	0.231	1.184
Large	3	ASH62.2_2016	E	10	105	570	1907	2904	189	5570	5693	0.249	1.099
Large	3	ASH62.2_2016	E	12	99	584	5132	2537	179	8432	8744	0.241	1.136
Large	3	ASH62.2_2016	E	13	103	751	5128	3458	186	9524	9807	0.244	1.117
Large	3	ASH62.2_2016	E	16	104	548	11709	1445	187	13888	14261	0.257	1.071
Large	3	T24_2019	B	1	83	229	9968	0	301	10497	9451	0.333	0.824
Large	3	T24_2019	B	3	85	283	4699	948	305	6235	5836	0.321	0.854
Large	3	T24_2019	B	10	92	575	2416	2868	331	6190	5961	0.316	0.877
Large	3	T24_2019	B	12	86	599	6088	2506	312	9504	8992	0.326	0.848
Large	3	T24_2019	B	13	90	771	6048	3462	325	10606	10167	0.315	0.875

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	3	T24_2019	B	16	91	591	13921	1404	327	16243	14658	0.352	0.792
Large	3	T24_2019	E	1	107	198	8618	0	193	9010	9301	0.256	1.065
Large	3	T24_2019	E	3	108	283	4049	1028	195	5555	5698	0.255	1.070
Large	3	T24_2019	E	10	111	570	1970	2895	201	5636	5683	0.264	1.036
Large	3	T24_2019	E	12	109	585	5291	2526	196	8598	8712	0.261	1.046
Large	3	T24_2019	E	13	111	753	5266	3457	200	9676	9792	0.261	1.045
Large	3	T24_2019	E	16	111	549	11890	1431	200	14071	14156	0.270	1.016
Large	3	BuilderPractice	B	1	89	234	10206	0	321	10761	9472	0.346	0.793
Large	3	BuilderPractice	B	3	89	283	4795	937	321	6337	5847	0.331	0.827
Large	3	BuilderPractice	B	10	89	575	2385	2874	321	6155	5964	0.309	0.896
Large	3	BuilderPractice	B	12	89	599	6151	2503	321	9574	8996	0.332	0.832
Large	3	BuilderPractice	B	13	89	771	6024	3462	321	10578	10164	0.313	0.881
Large	3	BuilderPractice	B	16	89	590	13850	1407	321	16168	14663	0.349	0.800
Large	3	BuilderPractice	E	1	89	185	8076	0	161	8422	9335	0.222	1.235
Large	3	BuilderPractice	E	3	89	283	3702	1068	161	5214	5687	0.214	1.276
Large	3	BuilderPractice	E	10	89	571	1765	2921	161	5418	5714	0.216	1.270
Large	3	BuilderPractice	E	12	89	583	4996	2547	161	8287	8787	0.222	1.233
Large	3	BuilderPractice	E	13	89	748	4937	3459	161	9305	9888	0.216	1.265
Large	3	BuilderPractice	E	16	89	546	11417	1470	161	13593	14518	0.234	1.186
Large	3	None	B	1	0	151	6578	0	0	6729	9003	0.138	2.039
Large	3	None	B	3	0	286	2914	1178	0	4378	5493	0.124	2.264
Large	3	None	B	10	0	576	1279	2954	0	4809	5770	0.102	2.973
Large	3	None	B	12	0	577	4101	2603	0	7282	8854	0.124	2.377
Large	3	None	B	13	0	732	4064	3438	0	8234	10308	0.105	2.833
Large	3	None	B	16	0	528	9756	1581	0	11866	16089	0.139	2.305
Large	3	None	E	1	0	151	6578	0	0	6729	9003	0.138	2.039
Large	3	None	E	3	0	286	2914	1178	0	4378	5493	0.124	2.264
Large	3	None	E	10	0	576	1279	2954	0	4809	5770	0.102	2.973
Large	3	None	E	12	0	577	4101	2603	0	7282	8854	0.124	2.377
Large	3	None	E	13	0	732	4064	3438	0	8234	10308	0.105	2.833
Large	3	None	E	16	0	528	9756	1581	0	11866	16089	0.139	2.305

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	5	T24_2008	B	1	64	246	10746	0	230	11222	9489	0.375	0.741
Large	5	T24_2008	B	3	64	286	5040	920	230	6475	5848	0.350	0.790
Large	5	T24_2008	B	10	64	574	2525	2846	230	6175	5995	0.315	0.903
Large	5	T24_2008	B	12	64	602	6454	2477	230	9763	9040	0.353	0.801
Large	5	T24_2008	B	13	64	772	6277	3436	230	10715	10267	0.322	0.876
Large	5	T24_2008	B	16	64	613	14898	1404	230	17145	15115	0.378	0.762
Large	5	T24_2008	E	1	64	211	9216	0	115	9542	9480	0.283	0.988
Large	5	T24_2008	E	3	64	285	4210	1015	115	5624	5777	0.260	1.072
Large	5	T24_2008	E	10	64	571	2058	2873	115	5617	5910	0.233	1.226
Large	5	T24_2008	E	12	64	590	5640	2505	115	8850	9049	0.265	1.073
Large	5	T24_2008	E	13	64	755	5474	3427	115	9770	10249	0.240	1.180
Large	5	T24_2008	E	16	64	585	13209	1463	115	15373	15609	0.288	1.035
Large	5	T24_2013	B	1	34	218	9501	0	121	9839	9397	0.305	0.917
Large	5	T24_2013	B	3	37	285	4429	991	132	5836	5759	0.287	0.967
Large	5	T24_2013	B	10	54	574	2390	2857	196	6016	5973	0.293	0.975
Large	5	T24_2013	B	12	41	595	5935	2502	148	9180	9034	0.300	0.952
Large	5	T24_2013	B	13	50	766	5966	3433	180	10345	10278	0.290	0.979
Large	5	T24_2013	B	16	51	604	14316	1425	185	16529	15203	0.350	0.832
Large	5	T24_2013	E	1	34	199	8673	0	60	8933	9345	0.257	1.094
Large	5	T24_2013	E	3	37	284	3965	1044	66	5360	5703	0.236	1.184
Large	5	T24_2013	E	10	54	571	2013	2877	98	5560	5921	0.223	1.291
Large	5	T24_2013	E	12	41	588	5408	2519	74	8590	9050	0.243	1.188
Large	5	T24_2013	E	13	50	752	5346	3423	90	9612	10293	0.225	1.272
Large	5	T24_2013	E	16	51	582	12962	1474	93	15110	15697	0.277	1.091
Large	5	Qtotal	B	1	117	298	12989	0	421	13708	9605	0.499	0.552
Large	5	Qtotal	B	3	117	289	6210	793	421	7713	5948	0.473	0.581
Large	5	Qtotal	B	10	117	577	3289	2788	421	7075	6078	0.438	0.638
Large	5	Qtotal	B	12	117	617	7706	2415	421	11160	9071	0.476	0.584
Large	5	Qtotal	B	13	117	796	7462	3440	421	12119	10232	0.445	0.624
Large	5	Qtotal	B	16	117	655	17365	1321	421	19762	14861	0.503	0.560
Large	5	Qtotal	E	1	117	228	9950	0	211	10389	9510	0.327	0.850

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Large	5	Qtotal	E	3	117	285	4675	964	211	6135	5880	0.305	0.903
Large	5	Qtotal	E	10	117	570	2360	2851	211	5992	5857	0.301	0.919
Large	5	Qtotal	E	12	117	594	6150	2471	211	9426	8964	0.323	0.860
Large	5	Qtotal	E	13	117	765	5981	3435	211	10391	10059	0.306	0.899
Large	5	Qtotal	E	16	117	599	14256	1406	211	16472	15057	0.345	0.820
Large	5	ASH62.2_2016	B	1	34	218	9501	0	121	9839	9397	0.305	0.917
Large	5	ASH62.2_2016	B	3	37	285	4429	991	132	5836	5759	0.287	0.967
Large	5	ASH62.2_2016	B	10	54	574	2390	2857	196	6016	5973	0.293	0.975
Large	5	ASH62.2_2016	B	12	41	595	5935	2502	148	9180	9034	0.300	0.952
Large	5	ASH62.2_2016	B	13	50	766	5966	3433	180	10345	10278	0.290	0.979
Large	5	ASH62.2_2016	B	16	51	604	14316	1425	185	16529	15203	0.350	0.832
Large	5	ASH62.2_2016	E	1	57	209	9101	0	104	9413	9449	0.278	1.007
Large	5	ASH62.2_2016	E	3	62	285	4193	1017	111	5605	5773	0.258	1.080
Large	5	ASH62.2_2016	E	10	83	571	2157	2867	150	5745	5890	0.256	1.102
Large	5	ASH62.2_2016	E	12	68	590	5678	2503	122	8893	9045	0.269	1.055
Large	5	ASH62.2_2016	E	13	78	758	5609	3430	141	9938	10198	0.256	1.092
Large	5	ASH62.2_2016	E	16	80	590	13535	1448	145	15718	15462	0.304	0.964
Large	5	T24_2019	B	1	83	267	11631	0	301	12199	9573	0.421	0.657
Large	5	T24_2019	B	3	85	286	5503	869	305	6963	5894	0.398	0.692
Large	5	T24_2019	B	10	92	576	2930	2815	331	6652	6045	0.380	0.740
Large	5	T24_2019	B	12	86	608	6987	2451	312	10358	9052	0.406	0.690
Large	5	T24_2019	B	13	90	784	6864	3439	325	11412	10246	0.383	0.729
Large	5	T24_2019	B	16	91	634	16139	1361	327	18462	14955	0.441	0.643
Large	5	T24_2019	E	1	107	228	9930	0	193	10351	9625	0.318	0.875
Large	5	T24_2019	E	3	108	285	4599	973	195	6052	5881	0.296	0.933
Large	5	T24_2019	E	10	111	570	2325	2854	201	5950	5865	0.293	0.947
Large	5	T24_2019	E	12	109	593	6075	2477	196	9341	8984	0.313	0.889
Large	5	T24_2019	E	13	111	763	5921	3435	200	10319	10084	0.297	0.927
Large	5	T24_2019	E	16	111	598	14148	1413	200	16359	15129	0.338	0.841
Large	5	BuilderPractice	B	1	89	273	11883	0	321	12477	9594	0.434	0.637
Large	5	BuilderPractice	B	3	89	286	5595	857	321	7060	5898	0.409	0.674

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Large	5	BuilderPractice	B	10	89	576	2896	2819	321	6612	6046	0.374	0.753
Large	5	BuilderPractice	B	12	89	609	7048	2448	321	10427	9053	0.412	0.680
Large	5	BuilderPractice	B	13	89	784	6844	3439	321	11388	10246	0.381	0.734
Large	5	BuilderPractice	B	16	89	633	16070	1364	321	18388	14963	0.438	0.649
Large	5	BuilderPractice	E	1	89	221	9645	0	161	10027	9577	0.304	0.918
Large	5	BuilderPractice	E	3	89	285	4434	991	161	5871	5846	0.280	0.989
Large	5	BuilderPractice	E	10	89	571	2191	2864	161	5786	5887	0.263	1.069
Large	5	BuilderPractice	E	12	89	592	5883	2489	161	9124	9017	0.291	0.964
Large	5	BuilderPractice	E	13	89	760	5718	3432	161	10070	10170	0.269	1.034
Large	5	BuilderPractice	E	16	89	593	13715	1439	161	15907	15373	0.313	0.927
Large	5	None	B	1	0	186	8103	0	0	8289	9220	0.227	1.248
Large	5	None	B	3	0	286	3655	1087	0	5028	5619	0.203	1.386
Large	5	None	B	10	0	572	1708	2901	0	5181	5894	0.168	1.830
Large	5	None	B	12	0	585	4992	2547	0	8124	9032	0.205	1.458
Large	5	None	B	13	0	743	4874	3416	0	9033	10449	0.174	1.733
Large	5	None	B	16	0	567	11959	1520	0	14046	16243	0.230	1.406
Large	5	None	E	1	0	186	8103	0	0	8289	9220	0.227	1.248
Large	5	None	E	3	0	286	3655	1087	0	5028	5619	0.203	1.386
Large	5	None	E	10	0	572	1708	2901	0	5181	5894	0.168	1.830
Large	5	None	E	12	0	585	4992	2547	0	8124	9032	0.205	1.458
Large	5	None	E	13	0	743	4874	3416	0	9033	10449	0.174	1.733
Large	5	None	E	16	0	567	11959	1520	0	14046	16243	0.230	1.406
Med	0.6	T24_2008	B	1	50	170	7434	0	181	7786	9223	0.182	1.600
Med	0.6	T24_2008	B	3	50	246	3565	884	181	4876	5549	0.180	1.618
Med	0.6	T24_2008	B	10	50	480	1533	2424	181	4619	5086	0.176	1.655
Med	0.6	T24_2008	B	12	50	501	4585	2135	181	7402	8241	0.180	1.620
Med	0.6	T24_2008	B	13	50	639	4599	2886	181	8305	9241	0.177	1.650
Med	0.6	T24_2008	B	16	50	457	9128	1281	181	11047	12775	0.182	1.599
Med	0.6	T24_2008	E	1	50	163	7096	0	91	7349	8956	0.160	1.821
Med	0.6	T24_2008	E	3	50	250	3435	920	91	4695	5440	0.160	1.820
Med	0.6	T24_2008	E	10	50	480	1425	2435	91	4431	4863	0.160	1.820

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	0.6	T24_2008	E	12	50	497	4361	2140	91	7088	7941	0.160	1.821
Med	0.6	T24_2008	E	13	50	632	4368	2878	91	7968	8874	0.160	1.821
Med	0.6	T24_2008	E	16	50	446	8572	1293	91	10401	12239	0.160	1.821
Med	0.6	T24_2013	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	T24_2013	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	T24_2013	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	T24_2013	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983
Med	0.6	T24_2013	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	T24_2013	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	T24_2013	E	1	86	196	8557	0	155	8908	9140	0.273	1.066
Med	0.6	T24_2013	E	3	86	248	4200	818	155	5422	5525	0.274	1.063
Med	0.6	T24_2013	E	10	87	476	1889	2374	158	4896	4945	0.278	1.049
Med	0.6	T24_2013	E	12	87	502	5152	2081	156	7890	8000	0.275	1.060
Med	0.6	T24_2013	E	13	87	645	5132	2867	157	8800	8901	0.277	1.052
Med	0.6	T24_2013	E	16	87	470	10266	1213	157	12106	12308	0.277	1.051
Med	0.6	Qtotal	B	1	92	212	9236	0	331	9778	9436	0.316	0.922
Med	0.6	Qtotal	B	3	92	242	4500	749	331	5822	5678	0.313	0.929
Med	0.6	Qtotal	B	10	92	482	2075	2386	331	5274	5196	0.309	0.943
Med	0.6	Qtotal	B	12	92	509	5593	2069	331	8502	8332	0.313	0.930
Med	0.6	Qtotal	B	13	92	656	5522	2882	331	9391	9243	0.309	0.941
Med	0.6	Qtotal	B	16	92	488	11221	1193	331	13233	12829	0.317	0.920
Med	0.6	Qtotal	E	1	92	202	8794	0	165	9161	9161	0.291	1.000
Med	0.6	Qtotal	E	3	92	248	4324	803	165	5540	5540	0.291	1.000
Med	0.6	Qtotal	E	10	92	480	1916	2396	165	4957	4957	0.291	1.000
Med	0.6	Qtotal	E	12	92	502	5259	2072	165	7999	7999	0.291	1.000
Med	0.6	Qtotal	E	13	92	646	5222	2863	165	8897	8897	0.291	1.000
Med	0.6	Qtotal	E	16	92	473	10466	1204	165	12308	12308	0.291	1.000
Med	0.6	ASH62.2_2016	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	ASH62.2_2016	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	ASH62.2_2016	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	ASH62.2_2016	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	0.6	ASH62.2_2016	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	ASH62.2_2016	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	ASH62.2_2016	E	1	91	201	8779	0	165	9145	9160	0.290	1.004
Med	0.6	ASH62.2_2016	E	3	91	248	4317	804	165	5534	5540	0.290	1.004
Med	0.6	ASH62.2_2016	E	10	91	480	1914	2396	165	4955	4958	0.290	1.002
Med	0.6	ASH62.2_2016	E	12	91	502	5251	2072	165	7990	7996	0.290	1.003
Med	0.6	ASH62.2_2016	E	13	91	646	5217	2863	165	8891	8896	0.290	1.002
Med	0.6	ASH62.2_2016	E	16	91	473	10457	1204	165	12299	12309	0.290	1.002
Med	0.6	T24_2019	B	1	86	206	8973	0	310	9488	9403	0.297	0.979
Med	0.6	T24_2019	B	3	86	242	4359	768	311	5680	5651	0.296	0.985
Med	0.6	T24_2019	B	10	87	477	2039	2363	315	5194	5176	0.295	0.987
Med	0.6	T24_2019	B	12	87	508	5459	2080	312	8359	8319	0.296	0.983
Med	0.6	T24_2019	B	13	87	654	5422	2882	314	9272	9243	0.295	0.988
Med	0.6	T24_2019	B	16	87	485	10995	1202	314	12997	12825	0.302	0.964
Med	0.6	T24_2019	E	1	91	201	8779	0	165	9145	9160	0.290	1.004
Med	0.6	T24_2019	E	3	91	248	4317	804	165	5534	5540	0.290	1.004
Med	0.6	T24_2019	E	10	91	480	1914	2396	165	4955	4958	0.290	1.002
Med	0.6	T24_2019	E	12	91	502	5251	2072	165	7990	7996	0.290	1.003
Med	0.6	T24_2019	E	13	91	646	5217	2863	165	8891	8896	0.290	1.002
Med	0.6	T24_2019	E	16	91	473	10457	1204	165	12299	12309	0.290	1.002
Med	0.6	BuilderPractice	B	1	70	190	8295	0	254	8740	9336	0.247	1.178
Med	0.6	BuilderPractice	B	3	70	244	4004	819	254	5320	5610	0.245	1.189
Med	0.6	BuilderPractice	B	10	70	478	1807	2393	254	4932	5147	0.241	1.210
Med	0.6	BuilderPractice	B	12	70	505	5071	2104	254	7934	8293	0.245	1.190
Med	0.6	BuilderPractice	B	13	70	647	5046	2885	254	8833	9241	0.241	1.207
Med	0.6	BuilderPractice	B	16	70	472	10163	1236	254	12126	12825	0.248	1.176
Med	0.6	BuilderPractice	E	1	70	181	7897	0	127	8206	9052	0.224	1.301
Med	0.6	BuilderPractice	E	3	70	249	3855	865	127	5096	5489	0.224	1.301
Med	0.6	BuilderPractice	E	10	70	477	1655	2402	127	4661	4889	0.224	1.301
Med	0.6	BuilderPractice	E	12	70	499	4799	2107	127	7532	7979	0.224	1.301
Med	0.6	BuilderPractice	E	13	70	639	4800	2872	127	8439	8913	0.224	1.301

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	0.6	BuilderPractice	E	16	70	459	9491	1247	127	11324	12275	0.224	1.301
Med	0.6	None	B	1	0	126	5486	0	0	5612	8833	0.019	15.573
Med	0.6	None	B	3	0	257	2576	1064	0	3896	5630	0.017	16.896
Med	0.6	None	B	10	0	489	927	2515	0	3932	4494	0.014	21.515
Med	0.6	None	B	12	0	493	3455	2215	0	6163	8002	0.018	16.992
Med	0.6	None	B	13	0	620	3475	2892	0	6987	9370	0.015	20.496
Med	0.6	None	B	16	0	421	6647	1419	0	8487	13729	0.019	17.118
Med	0.6	None	E	1	0	126	5486	0	0	5612	8833	0.019	15.573
Med	0.6	None	E	3	0	257	2576	1064	0	3896	5630	0.017	16.896
Med	0.6	None	E	10	0	489	927	2515	0	3932	4494	0.014	21.515
Med	0.6	None	E	12	0	493	3455	2215	0	6163	8002	0.018	16.992
Med	0.6	None	E	13	0	620	3475	2892	0	6987	9370	0.015	20.496
Med	0.6	None	E	16	0	421	6647	1419	0	8487	13729	0.019	17.118
Med	1	T24_2008	B	1	50	174	7584	0	181	7940	9212	0.194	1.499
Med	1	T24_2008	B	3	50	245	3635	873	181	4934	5534	0.191	1.523
Med	1	T24_2008	B	10	50	479	1574	2416	181	4652	5080	0.185	1.574
Med	1	T24_2008	B	12	50	501	4682	2128	181	7492	8248	0.191	1.524
Med	1	T24_2008	B	13	50	640	4677	2882	181	8381	9238	0.186	1.565
Med	1	T24_2008	B	16	50	461	9366	1274	181	11282	12846	0.195	1.501
Med	1	T24_2008	E	1	50	163	7107	0	91	7360	8971	0.160	1.818
Med	1	T24_2008	E	3	50	249	3438	918	91	4697	5441	0.160	1.819
Med	1	T24_2008	E	10	50	480	1431	2433	91	4434	4866	0.160	1.816
Med	1	T24_2008	E	12	50	496	4373	2138	91	7098	7955	0.160	1.817
Med	1	T24_2008	E	13	50	632	4378	2876	91	7977	8890	0.160	1.820
Med	1	T24_2008	E	16	50	447	8599	1292	91	10429	12286	0.160	1.819
Med	1	T24_2013	B	1	82	206	8975	0	296	9477	9392	0.297	0.979
Med	1	T24_2013	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	T24_2013	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	T24_2013	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	T24_2013	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	T24_2013	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	1	T24_2013	E	1	82	193	8401	0	148	8742	9127	0.261	1.115
Med	1	T24_2013	E	3	83	248	4123	829	149	5350	5522	0.262	1.110
Med	1	T24_2013	E	10	85	476	1863	2377	152	4868	4948	0.269	1.083
Med	1	T24_2013	E	12	83	501	5087	2085	150	7822	8006	0.264	1.104
Med	1	T24_2013	E	13	84	644	5080	2867	152	8742	8912	0.267	1.090
Med	1	T24_2013	E	16	84	469	10156	1218	152	11995	12332	0.267	1.088
Med	1	Qtotal	B	1	92	216	9408	0	331	9955	9443	0.328	0.888
Med	1	Qtotal	B	3	92	242	4589	739	331	5901	5684	0.324	0.897
Med	1	Qtotal	B	10	92	481	2118	2379	331	5309	5191	0.318	0.916
Med	1	Qtotal	B	12	92	510	5685	2062	331	8587	8328	0.325	0.898
Med	1	Qtotal	B	13	92	657	5602	2879	331	9469	9243	0.319	0.913
Med	1	Qtotal	B	16	92	493	11455	1188	331	13466	12866	0.329	0.887
Med	1	Qtotal	E	1	92	202	8801	0	165	9168	9168	0.291	1.000
Med	1	Qtotal	E	3	92	248	4327	802	165	5542	5542	0.291	1.000
Med	1	Qtotal	E	10	92	480	1921	2395	165	4960	4960	0.291	1.000
Med	1	Qtotal	E	12	92	502	5265	2070	165	8003	8003	0.291	1.000
Med	1	Qtotal	E	13	92	646	5228	2862	165	8901	8901	0.291	1.000
Med	1	Qtotal	E	16	92	474	10483	1203	165	12325	12325	0.291	1.000
Med	1	ASH62.2_2016	B	1	82	206	8975	0	296	9477	9392	0.297	0.979
Med	1	ASH62.2_2016	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	ASH62.2_2016	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	ASH62.2_2016	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	ASH62.2_2016	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	ASH62.2_2016	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957
Med	1	ASH62.2_2016	E	1	91	201	8761	0	164	9126	9166	0.288	1.011
Med	1	ASH62.2_2016	E	3	91	248	4307	804	164	5523	5540	0.288	1.010
Med	1	ASH62.2_2016	E	10	91	480	1915	2395	164	4954	4960	0.289	1.006
Med	1	ASH62.2_2016	E	12	91	502	5250	2072	164	7988	8005	0.288	1.009
Med	1	ASH62.2_2016	E	13	91	646	5215	2862	164	8887	8901	0.289	1.007
Med	1	ASH62.2_2016	E	16	91	473	10458	1205	164	12300	12328	0.289	1.007
Med	1	T24_2019	B	1	82	206	8975	0	296	9477	9392	0.297	0.979

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	1	T24_2019	B	3	83	242	4360	768	298	5668	5643	0.295	0.987
Med	1	T24_2019	B	10	85	477	2049	2360	305	5190	5174	0.295	0.987
Med	1	T24_2019	B	12	83	508	5470	2078	300	8355	8314	0.297	0.982
Med	1	T24_2019	B	13	84	654	5433	2879	303	9269	9243	0.295	0.989
Med	1	T24_2019	B	16	84	487	11081	1202	304	13074	12864	0.305	0.957
Med	1	T24_2019	E	1	91	201	8761	0	164	9126	9166	0.288	1.011
Med	1	T24_2019	E	3	91	248	4307	804	164	5523	5540	0.288	1.010
Med	1	T24_2019	E	10	91	480	1915	2395	164	4954	4960	0.289	1.006
Med	1	T24_2019	E	12	91	502	5250	2072	164	7988	8005	0.288	1.009
Med	1	T24_2019	E	13	91	646	5215	2862	164	8887	8901	0.289	1.007
Med	1	T24_2019	E	16	91	473	10458	1205	164	12300	12328	0.289	1.007
Med	1	BuilderPractice	B	1	70	194	8456	0	254	8904	9336	0.259	1.123
Med	1	BuilderPractice	B	3	70	243	4092	807	254	5397	5617	0.256	1.137
Med	1	BuilderPractice	B	10	70	479	1874	2385	254	4992	5173	0.250	1.166
Med	1	BuilderPractice	B	12	70	505	5168	2097	254	8025	8297	0.256	1.138
Med	1	BuilderPractice	B	13	70	648	5124	2882	254	8908	9238	0.251	1.162
Med	1	BuilderPractice	B	16	70	477	10405	1231	254	12367	12881	0.260	1.122
Med	1	BuilderPractice	E	1	70	181	7909	0	127	8218	9067	0.224	1.300
Med	1	BuilderPractice	E	3	70	249	3857	863	127	5096	5489	0.224	1.300
Med	1	BuilderPractice	E	10	70	477	1666	2401	127	4671	4900	0.224	1.300
Med	1	BuilderPractice	E	12	70	499	4807	2106	127	7539	7986	0.224	1.300
Med	1	BuilderPractice	E	13	70	639	4809	2871	127	8446	8922	0.224	1.301
Med	1	BuilderPractice	E	16	70	459	9513	1247	127	11347	12304	0.224	1.301
Med	1	None	B	1	0	129	5617	0	0	5745	8733	0.032	9.427
Med	1	None	B	3	0	256	2649	1051	0	3956	5508	0.029	10.215
Med	1	None	B	10	0	488	981	2502	0	3972	4780	0.024	13.034
Med	1	None	B	12	0	494	3538	2207	0	6239	8019	0.029	10.310
Med	1	None	B	13	0	620	3548	2887	0	7055	9217	0.025	12.388
Med	1	None	B	16	0	425	6885	1405	0	8715	13910	0.032	10.402
Med	1	None	E	1	0	129	5617	0	0	5745	8733	0.032	9.427
Med	1	None	E	3	0	256	2649	1051	0	3956	5508	0.029	10.215

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	1	None	E	10	0	488	981	2502	0	3972	4780	0.024	13.034
Med	1	None	E	12	0	494	3538	2207	0	6239	8019	0.029	10.310
Med	1	None	E	13	0	620	3548	2887	0	7055	9217	0.025	12.388
Med	1	None	E	16	0	425	6885	1405	0	8715	13910	0.032	10.402
Med	2	T24_2008	B	1	50	183	7981	0	181	8346	9225	0.225	1.298
Med	2	T24_2008	B	3	50	245	3832	845	181	5104	5539	0.220	1.330
Med	2	T24_2008	B	10	50	478	1702	2396	181	4758	5104	0.209	1.405
Med	2	T24_2008	B	12	50	503	4922	2108	181	7714	8264	0.221	1.330
Med	2	T24_2008	B	13	50	642	4875	2874	181	8573	9238	0.211	1.390
Med	2	T24_2008	B	16	50	472	9979	1258	181	11891	13029	0.226	1.305
Med	2	T24_2008	E	1	50	164	7163	0	91	7418	9027	0.162	1.794
Med	2	T24_2008	E	3	50	249	3458	912	91	4710	5453	0.161	1.805
Med	2	T24_2008	E	10	50	479	1453	2424	91	4446	4882	0.162	1.803
Med	2	T24_2008	E	12	50	496	4422	2131	91	7139	8000	0.163	1.789
Med	2	T24_2008	E	13	50	632	4410	2872	91	8005	8927	0.161	1.809
Med	2	T24_2008	E	16	50	449	8712	1290	91	10541	12464	0.161	1.808
Med	2	T24_2013	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	T24_2013	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	T24_2013	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	T24_2013	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	T24_2013	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	T24_2013	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	T24_2013	E	1	73	184	8039	0	131	8355	9103	0.232	1.252
Med	2	T24_2013	E	3	73	248	3938	850	132	5169	5506	0.234	1.244
Med	2	T24_2013	E	10	77	476	1771	2383	140	4769	4922	0.247	1.178
Med	2	T24_2013	E	12	74	500	4932	2093	134	7659	8020	0.238	1.224
Med	2	T24_2013	E	13	76	641	4957	2866	138	8602	8946	0.243	1.198
Med	2	T24_2013	E	16	77	465	9895	1233	138	11731	12413	0.244	1.191
Med	2	Qtotal	B	1	92	226	9839	0	331	10395	9461	0.359	0.813
Med	2	Qtotal	B	3	92	242	4822	713	331	6107	5706	0.352	0.827
Med	2	Qtotal	B	10	92	481	2261	2360	331	5432	5212	0.341	0.856

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	2	Qtotal	B	12	92	512	5927	2043	331	8812	8333	0.353	0.827
Med	2	Qtotal	B	13	92	660	5833	2869	331	9693	9270	0.343	0.851
Med	2	Qtotal	B	16	92	503	12039	1173	331	14046	12952	0.360	0.814
Med	2	Qtotal	E	1	92	203	8830	0	165	9198	9188	0.292	0.997
Med	2	Qtotal	E	3	92	247	4336	798	165	5547	5544	0.292	0.998
Med	2	Qtotal	E	10	92	479	1936	2389	165	4969	4966	0.292	0.997
Med	2	Qtotal	E	12	92	502	5295	2066	165	8029	8023	0.292	0.997
Med	2	Qtotal	E	13	92	646	5255	2859	165	8925	8925	0.291	1.000
Med	2	Qtotal	E	16	92	475	10558	1202	165	12400	12396	0.291	0.999
Med	2	ASH62.2_2016	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	ASH62.2_2016	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	ASH62.2_2016	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	ASH62.2_2016	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	ASH62.2_2016	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	ASH62.2_2016	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	ASH62.2_2016	E	1	88	199	8669	0	158	9026	9176	0.280	1.041
Med	2	ASH62.2_2016	E	3	88	247	4258	808	159	5471	5538	0.280	1.039
Med	2	ASH62.2_2016	E	10	89	479	1912	2392	161	4945	4967	0.285	1.021
Med	2	ASH62.2_2016	E	12	88	502	5231	2071	159	7963	8027	0.282	1.033
Med	2	ASH62.2_2016	E	13	89	645	5202	2859	161	8867	8923	0.283	1.028
Med	2	ASH62.2_2016	E	16	89	474	10452	1207	161	12294	12400	0.284	1.026
Med	2	T24_2019	B	1	73	206	8978	0	262	9446	9368	0.298	0.981
Med	2	T24_2019	B	3	73	243	4364	770	265	5641	5628	0.294	0.993
Med	2	T24_2019	B	10	77	476	2073	2352	279	5180	5166	0.296	0.989
Med	2	T24_2019	B	12	74	508	5499	2070	268	8345	8302	0.298	0.981
Med	2	T24_2019	B	13	76	653	5464	2871	276	9264	9245	0.294	0.992
Med	2	T24_2019	B	16	77	492	11298	1203	277	13271	12970	0.312	0.941
Med	2	T24_2019	E	1	88	199	8669	0	158	9026	9176	0.280	1.041
Med	2	T24_2019	E	3	88	247	4258	808	159	5471	5538	0.280	1.039
Med	2	T24_2019	E	10	89	479	1912	2392	161	4945	4967	0.285	1.021
Med	2	T24_2019	E	12	88	502	5231	2071	159	7963	8027	0.282	1.033

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	2	T24_2019	E	13	89	645	5202	2859	161	8867	8923	0.283	1.028
Med	2	T24_2019	E	16	89	474	10452	1207	161	12294	12400	0.284	1.026
Med	2	BuilderPractice	B	1	70	204	8877	0	254	9335	9358	0.290	1.006
Med	2	BuilderPractice	B	3	70	243	4295	779	254	5570	5617	0.284	1.026
Med	2	BuilderPractice	B	10	70	477	1978	2366	254	5075	5157	0.273	1.070
Med	2	BuilderPractice	B	12	70	507	5399	2078	254	8238	8294	0.285	1.026
Med	2	BuilderPractice	B	13	70	650	5330	2871	254	9106	9244	0.275	1.062
Med	2	BuilderPractice	B	16	70	487	10989	1216	254	12947	12987	0.291	1.008
Med	2	BuilderPractice	E	1	70	182	7947	0	127	8256	9094	0.225	1.292
Med	2	BuilderPractice	E	3	70	248	3871	858	127	5104	5494	0.225	1.296
Med	2	BuilderPractice	E	10	70	476	1683	2392	127	4678	4906	0.225	1.294
Med	2	BuilderPractice	E	12	70	499	4851	2099	127	7577	8023	0.225	1.292
Med	2	BuilderPractice	E	13	70	639	4835	2867	127	8469	8949	0.224	1.299
Med	2	BuilderPractice	E	16	70	461	9608	1245	127	11442	12418	0.224	1.298
Med	2	None	B	1	0	137	5967	0	0	6104	8798	0.063	4.776
Med	2	None	B	3	0	254	2832	1015	0	4101	5407	0.058	5.168
Med	2	None	B	10	0	484	1082	2471	0	4037	4780	0.048	6.608
Med	2	None	B	12	0	494	3757	2183	0	6434	8073	0.059	5.245
Med	2	None	B	13	0	621	3755	2870	0	7247	9257	0.049	6.264
Med	2	None	B	16	0	434	7481	1374	0	9288	14122	0.063	5.294
Med	2	None	E	1	0	137	5967	0	0	6104	8798	0.063	4.776
Med	2	None	E	3	0	254	2832	1015	0	4101	5407	0.058	5.168
Med	2	None	E	10	0	484	1082	2471	0	4037	4780	0.048	6.608
Med	2	None	E	12	0	494	3757	2183	0	6434	8073	0.059	5.245
Med	2	None	E	13	0	621	3755	2870	0	7247	9257	0.049	6.264
Med	2	None	E	16	0	434	7481	1374	0	9288	14122	0.063	5.294
Med	3	T24_2008	B	1	50	193	8422	0	181	8797	9292	0.256	1.145
Med	3	T24_2008	B	3	50	244	4049	817	181	5291	5565	0.248	1.182
Med	3	T24_2008	B	10	50	477	1839	2377	181	4875	5138	0.232	1.271
Med	3	T24_2008	B	12	50	504	5152	2089	181	7927	8269	0.250	1.182
Med	3	T24_2008	B	13	50	645	5080	2866	181	8773	9253	0.235	1.252

						Annual HVAC Energy Use (kWh/year)							
Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	3	T24_2008	B	16	50	483	10579	1243	181	12486	13167	0.257	1.157
Med	3	T24_2008	E	1	50	167	7264	0	91	7521	9119	0.167	1.750
Med	3	T24_2008	E	3	50	248	3492	903	91	4734	5472	0.164	1.780
Med	3	T24_2008	E	10	50	478	1494	2413	91	4475	4917	0.165	1.774
Med	3	T24_2008	E	12	50	496	4509	2121	91	7217	8069	0.169	1.729
Med	3	T24_2008	E	13	50	633	4480	2867	91	8071	9000	0.165	1.770
Med	3	T24_2008	E	16	50	457	9113	1286	91	10947	12924	0.172	1.710
Med	3	T24_2013	B	1	63	206	8983	0	228	9418	9351	0.298	0.983
Med	3	T24_2013	B	3	64	243	4364	770	232	5609	5608	0.293	1.000
Med	3	T24_2013	B	10	70	475	2097	2345	254	5171	5160	0.296	0.992
Med	3	T24_2013	B	12	66	507	5528	2064	237	8337	8296	0.299	0.982
Med	3	T24_2013	B	13	69	653	5496	2864	248	9261	9252	0.294	0.996
Med	3	T24_2013	B	16	69	497	11526	1203	250	13477	13091	0.319	0.927
Med	3	T24_2013	E	1	63	177	7728	0	114	8019	9118	0.206	1.418
Med	3	T24_2013	E	3	64	247	3755	867	116	4985	5473	0.207	1.408
Med	3	T24_2013	E	10	70	475	1712	2383	127	4697	4926	0.226	1.288
Med	3	T24_2013	E	12	66	498	4812	2099	119	7528	8059	0.215	1.359
Med	3	T24_2013	E	13	69	639	4844	2863	124	8470	8982	0.221	1.319
Med	3	T24_2013	E	16	69	464	9716	1246	125	11551	12591	0.223	1.307
Med	3	Qtotal	B	1	92	236	10269	0	331	10835	9479	0.389	0.751
Med	3	Qtotal	B	3	92	242	5021	687	331	6280	5701	0.380	0.768
Med	3	Qtotal	B	10	92	481	2395	2344	331	5551	5229	0.365	0.804
Med	3	Qtotal	B	12	92	513	6162	2025	331	9031	8335	0.382	0.767
Med	3	Qtotal	B	13	92	663	6054	2861	331	9909	9289	0.367	0.796
Med	3	Qtotal	B	16	92	514	12617	1160	331	14621	13027	0.390	0.753
Med	3	Qtotal	E	1	92	204	8890	0	165	9259	9223	0.294	0.991
Med	3	Qtotal	E	3	92	247	4354	792	165	5558	5549	0.293	0.995
Med	3	Qtotal	E	10	92	478	1956	2380	165	4980	4973	0.293	0.993
Med	3	Qtotal	E	12	92	502	5346	2059	165	8072	8051	0.294	0.990
Med	3	Qtotal	E	13	92	646	5292	2855	165	8959	8953	0.292	0.997
Med	3	Qtotal	E	16	92	477	10661	1201	165	12505	12489	0.292	0.996

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	3	ASH62.2_2016	B	1	63	206	8983	0	228	9418	9351	0.298	0.983
Med	3	ASH62.2_2016	B	3	64	243	4364	770	232	5609	5608	0.293	1.000
Med	3	ASH62.2_2016	B	10	70	475	2097	2345	254	5171	5160	0.296	0.992
Med	3	ASH62.2_2016	B	12	66	507	5528	2064	237	8337	8296	0.299	0.982
Med	3	ASH62.2_2016	B	13	69	653	5496	2864	248	9261	9252	0.294	0.996
Med	3	ASH62.2_2016	B	16	69	497	11526	1203	250	13477	13091	0.319	0.927
Med	3	ASH62.2_2016	E	1	83	196	8525	0	149	8870	9193	0.267	1.093
Med	3	ASH62.2_2016	E	3	84	247	4182	813	151	5393	5538	0.267	1.091
Med	3	ASH62.2_2016	E	10	87	474	1926	2360	156	4916	4966	0.278	1.049
Med	3	ASH62.2_2016	E	12	84	501	5194	2071	152	7918	8053	0.272	1.072
Med	3	ASH62.2_2016	E	13	86	644	5176	2858	155	8833	8955	0.274	1.062
Med	3	ASH62.2_2016	E	16	86	474	10430	1211	156	12270	12510	0.275	1.058
Med	3	T24_2019	B	1	73	216	9426	0	262	9905	9414	0.329	0.891
Med	3	T24_2019	B	3	73	242	4584	742	265	5834	5646	0.322	0.908
Med	3	T24_2019	B	10	77	476	2210	2335	279	5301	5189	0.319	0.920
Med	3	T24_2019	B	12	74	509	5747	2050	268	8575	8317	0.327	0.898
Med	3	T24_2019	B	13	76	656	5671	2864	276	9467	9258	0.319	0.919
Med	3	T24_2019	B	16	77	503	11895	1189	277	13864	13072	0.342	0.861
Med	3	T24_2019	E	1	88	200	8729	0	158	9088	9212	0.282	1.034
Med	3	T24_2019	E	3	88	247	4275	802	159	5482	5542	0.281	1.035
Med	3	T24_2019	E	10	89	478	1934	2384	161	4958	4976	0.286	1.017
Med	3	T24_2019	E	12	88	501	5274	2064	159	7999	8047	0.284	1.025
Med	3	T24_2019	E	13	89	645	5238	2855	161	8899	8949	0.284	1.025
Med	3	T24_2019	E	16	89	476	10558	1205	161	12400	12497	0.285	1.023
Med	3	BuilderPractice	B	1	70	214	9319	0	254	9787	9400	0.321	0.912
Med	3	BuilderPractice	B	3	70	242	4504	751	254	5751	5626	0.312	0.936
Med	3	BuilderPractice	B	10	70	475	2098	2345	254	5172	5160	0.297	0.991
Med	3	BuilderPractice	B	12	70	508	5643	2056	254	8462	8305	0.314	0.935
Med	3	BuilderPractice	B	13	70	653	5532	2864	254	9303	9252	0.299	0.979
Med	3	BuilderPractice	B	16	70	498	11580	1201	254	13533	13088	0.322	0.917
Med	3	BuilderPractice	E	1	70	184	8014	0	127	8325	9144	0.228	1.279

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	3	BuilderPractice	E	3	70	247	3891	851	127	5117	5500	0.226	1.288
Med	3	BuilderPractice	E	10	70	475	1714	2384	127	4700	4927	0.227	1.287
Med	3	BuilderPractice	E	12	70	499	4903	2092	127	7621	8052	0.229	1.274
Med	3	BuilderPractice	E	13	70	639	4874	2863	127	8503	8979	0.226	1.290
Med	3	BuilderPractice	E	16	70	464	9758	1243	127	11592	12581	0.226	1.288
Med	3	None	B	1	0	145	6316	0	0	6461	8818	0.095	3.203
Med	3	None	B	3	0	252	3031	983	0	4266	5451	0.086	3.471
Med	3	None	B	10	0	482	1195	2446	0	4123	4875	0.072	4.446
Med	3	None	B	12	0	495	3984	2163	0	6642	8148	0.088	3.536
Med	3	None	B	13	0	623	3958	2859	0	7440	9287	0.074	4.211
Med	3	None	B	16	0	443	8072	1347	0	9863	14223	0.095	3.564
Med	3	None	E	1	0	145	6316	0	0	6461	8818	0.095	3.203
Med	3	None	E	3	0	252	3031	983	0	4266	5451	0.086	3.471
Med	3	None	E	10	0	482	1195	2446	0	4123	4875	0.072	4.446
Med	3	None	E	12	0	495	3984	2163	0	6642	8148	0.088	3.536
Med	3	None	E	13	0	623	3958	2859	0	7440	9287	0.074	4.211
Med	3	None	E	16	0	443	8072	1347	0	9863	14223	0.095	3.564
Med	5	T24_2008	B	1	50	213	9285	0	181	9679	9381	0.318	0.930
Med	5	T24_2008	B	3	50	243	4456	760	181	5639	5583	0.304	0.969
Med	5	T24_2008	B	10	50	475	2077	2338	181	5072	5156	0.279	1.072
Med	5	T24_2008	B	12	50	507	5646	2049	181	8384	8314	0.308	0.970
Med	5	T24_2008	B	13	50	650	5491	2849	181	9172	9281	0.284	1.047
Med	5	T24_2008	B	16	50	505	11766	1213	181	13665	13377	0.319	0.948
Med	5	T24_2008	E	1	50	182	7949	0	91	8222	9324	0.215	1.389
Med	5	T24_2008	E	3	50	246	3777	859	91	4972	5528	0.202	1.469
Med	5	T24_2008	E	10	50	475	1723	2375	91	4664	5066	0.195	1.530
Med	5	T24_2008	E	12	50	499	4957	2083	91	7630	8252	0.215	1.393
Med	5	T24_2008	E	13	50	637	4867	2847	91	8442	9215	0.198	1.490
Med	5	T24_2008	E	16	50	482	10359	1267	91	12199	13694	0.224	1.370
Med	5	T24_2013	B	1	44	207	9008	0	160	9375	9341	0.299	0.991
Med	5	T24_2013	B	3	46	243	4351	773	166	5533	5561	0.290	1.016

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	5	T24_2013	B	10	56	475	2165	2331	203	5174	5176	0.298	1.002
Med	5	T24_2013	B	12	49	507	5606	2052	175	8340	8314	0.302	0.989
Med	5	T24_2013	B	13	54	652	5567	2849	194	9261	9280	0.294	1.008
Med	5	T24_2013	B	16	55	508	11975	1205	197	13884	13350	0.333	0.907
Med	5	T24_2013	E	1	44	180	7837	0	80	8097	9271	0.209	1.434
Med	5	T24_2013	E	3	46	246	3741	863	83	4933	5513	0.197	1.506
Med	5	T24_2013	E	10	56	475	1754	2369	101	4699	5048	0.206	1.440
Med	5	T24_2013	E	12	49	499	4940	2085	88	7611	8255	0.212	1.412
Med	5	T24_2013	E	13	54	638	4898	2849	97	8482	9197	0.204	1.443
Med	5	T24_2013	E	16	55	483	10441	1261	98	12284	13606	0.230	1.321
Med	5	Qtotal	B	1	92	257	11187	0	331	11774	9553	0.451	0.652
Med	5	Qtotal	B	3	92	242	5448	635	331	6656	5716	0.436	0.672
Med	5	Qtotal	B	10	92	480	2639	2310	331	5760	5240	0.411	0.720
Med	5	Qtotal	B	12	92	517	6646	1987	331	9480	8351	0.440	0.671
Med	5	Qtotal	B	13	92	669	6486	2845	331	10331	9318	0.416	0.708
Med	5	Qtotal	B	16	92	536	13791	1133	331	15790	13174	0.452	0.657
Med	5	Qtotal	E	1	92	208	9057	0	165	9430	9317	0.301	0.972
Med	5	Qtotal	E	3	92	245	4424	777	165	5612	5580	0.297	0.983
Med	5	Qtotal	E	10	92	476	2027	2359	165	5027	5007	0.298	0.982
Med	5	Qtotal	E	12	92	502	5493	2041	165	8201	8122	0.304	0.963
Med	5	Qtotal	E	13	92	646	5396	2847	165	9054	9014	0.297	0.982
Med	5	Qtotal	E	16	92	489	11236	1196	165	13086	12888	0.305	0.960
Med	5	ASH62.2_2016	B	1	44	207	9008	0	160	9375	9341	0.299	0.991
Med	5	ASH62.2_2016	B	3	46	243	4351	773	166	5533	5561	0.290	1.016
Med	5	ASH62.2_2016	B	10	56	475	2165	2331	203	5174	5176	0.298	1.002
Med	5	ASH62.2_2016	B	12	49	507	5606	2052	175	8340	8314	0.302	0.989
Med	5	ASH62.2_2016	B	13	54	652	5567	2849	194	9261	9280	0.294	1.008
Med	5	ASH62.2_2016	B	16	55	508	11975	1205	197	13884	13350	0.333	0.907
Med	5	ASH62.2_2016	E	1	67	190	8281	0	121	8593	9347	0.239	1.236
Med	5	ASH62.2_2016	E	3	69	246	4006	832	124	5209	5587	0.232	1.266
Med	5	ASH62.2_2016	E	10	78	473	1922	2351	141	4887	5022	0.258	1.137

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year) Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total	Ventilation Rate (hr^{-1})	Relative Exposure
Med	5	ASH62.2_2016	E	12	71	500	5179	2067	129	7875	8184	0.252	1.169
Med	5	ASH62.2_2016	E	13	76	642	5146	2850	137	8775	9072	0.253	1.155
Med	5	ASH62.2_2016	E	16	77	487	10893	1223	138	12741	13168	0.271	1.093
Med	5	T24_2019	B	1	73	236	10285	0	262	10783	9465	0.390	0.755
Med	5	T24_2019	B	3	73	243	5019	690	265	6215	5675	0.378	0.777
Med	5	T24_2019	B	10	77	476	2482	2303	279	5540	5231	0.365	0.811
Med	5	T24_2019	B	12	74	513	6232	2014	268	9027	8341	0.385	0.770
Med	5	T24_2019	B	13	76	662	6126	2846	276	9911	9312	0.367	0.803
Med	5	T24_2019	B	16	77	525	13063	1161	277	15026	13228	0.404	0.738
Med	5	T24_2019	E	1	88	204	8908	0	158	9271	9314	0.289	1.011
Med	5	T24_2019	E	3	88	245	4345	786	159	5535	5572	0.286	1.021
Med	5	T24_2019	E	10	89	476	1988	2362	161	4987	4992	0.291	1.005
Med	5	T24_2019	E	12	88	502	5429	2047	159	8137	8125	0.295	0.994
Med	5	T24_2019	E	13	89	646	5352	2847	161	9006	9020	0.289	1.007
Med	5	T24_2019	E	16	89	489	11173	1200	161	13022	12926	0.300	0.980
Med	5	BuilderPractice	B	1	70	234	10188	0	254	10676	9462	0.383	0.770
Med	5	BuilderPractice	B	3	70	242	4947	698	254	6142	5665	0.368	0.798
Med	5	BuilderPractice	B	10	70	475	2373	2311	254	5414	5210	0.343	0.865
Med	5	BuilderPractice	B	12	70	512	6125	2020	254	8911	8329	0.372	0.797
Med	5	BuilderPractice	B	13	70	660	5987	2847	254	9748	9312	0.348	0.849
Med	5	BuilderPractice	B	16	70	520	12754	1173	254	14700	13257	0.384	0.779
Med	5	BuilderPractice	E	1	70	192	8356	0	127	8675	9335	0.246	1.201
Med	5	BuilderPractice	E	3	70	246	4027	829	127	5229	5584	0.235	1.246
Med	5	BuilderPractice	E	10	70	474	1860	2360	127	4821	5036	0.239	1.235
Med	5	BuilderPractice	E	12	70	500	5169	2068	127	7864	8189	0.250	1.179
Med	5	BuilderPractice	E	13	70	641	5076	2851	127	8695	9103	0.239	1.223
Med	5	BuilderPractice	E	16	70	486	10760	1235	127	12607	13283	0.259	1.152
Med	5	None	B	1	0	163	7100	0	0	7263	9036	0.157	1.948
Med	5	None	B	3	0	250	3407	924	0	4581	5461	0.143	2.108
Med	5	None	B	10	0	478	1416	2406	0	4299	4973	0.119	2.708
Med	5	None	B	12	0	497	4432	2125	0	7054	8216	0.147	2.156

Prototype	Airtightness (ACH_{50})	Fan Sizing Method	Fan Type	Climate Zone	Whole house fan Airflow (cfm)	Annual HVAC Energy Use (kWh/year)						Ventilation Rate (hr^{-1})	Relative Exposure
						Air Handler (AHU)	Heat	Cooling	Ventilation	Total	Normalized Total		
Med	5	None	B	13	0	628	4350	2843	0	7821	9315	0.123	2.562
Med	5	None	B	16	0	463	9255	1307	0	11025	14355	0.158	2.163
Med	5	None	E	1	0	163	7100	0	0	7263	9036	0.157	1.948
Med	5	None	E	3	0	250	3407	924	0	4581	5461	0.143	2.108
Med	5	None	E	10	0	478	1416	2406	0	4299	4973	0.119	2.708
Med	5	None	E	12	0	497	4432	2125	0	7054	8216	0.147	2.156
Med	5	None	E	13	0	628	4350	2843	0	7821	9315	0.123	2.562
Med	**5**	**None**	**E**	**16**	**0**	**463**	**9255**	**1307**	**0**	**11025**	**14355**	**0.158**	**2.163**

Table 15 Raw and normalized HVAC energy savings by sealing from 5 ACH_{50}.

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				Normalized Savings			
				3	2	1	0.6	3	2	1	0.6
Large	T24_2008	B	1	1632	2468	3292	3589	102	181	260	246
Large	T24_2008	B	3	743	1084	1421	1554	93	118	139	144
Large	T24_2008	B	10	437	623	824	904	94	109	143	157
Large	T24_2008	B	12	844	1275	1698	1870	68	115	154	175
Large	T24_2008	B	13	824	1213	1588	1731	116	156	175	168
Large	T24_2008	B	16	2216	3288	4379	4826	330	507	744	869
Large	T24_2008	E	1	1685	2363	2546	2574	161	306	455	489
Large	T24_2008	E	3	691	946	979	982	64	156	178	180
Large	T24_2008	E	10	393	556	607	616	135	264	331	344
Large	T24_2008	E	12	864	1278	1419	1442	166	400	551	583
Large	T24_2008	E	13	773	1136	1259	1278	175	406	565	598
Large	T24_2008	E	16	2158	3303	4000	4073	473	1139	1958	2084
Large	T24_2013	B	1	100	159	212	225	-5	-12	-34	-54
Large	T24_2013	B	3	-21	-37	-44	-50	-24	-46	-63	-74
Large	T24_2013	B	10	23	34	57	61	32	39	52	50
Large	T24_2013	B	12	65	97	131	139	55	68	71	65
Large	T24_2013	B	13	96	153	200	214	113	163	196	201

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	T24_2013	B	16	959	1433	1912	2098	524	758	984	1066
Large	T24_2013	E	1	1012	1062	455	204	3	204	216	224
Large	T24_2013	E	3	388	309	12	-120	-9	77	61	44
Large	T24_2013	E	10	220	198	87	37	180	285	312	316
Large	T24_2013	E	12	525	583	333	226	198	424	479	499
Large	T24_2013	E	13	473	464	243	146	320	549	632	653
Large	T24_2013	E	16	1730	2437	2169	1994	960	1908	2214	2258
Large	Qtotal	B	1	1583	2456	3305	3632	12	71	116	123
Large	Qtotal	B	3	718	1089	1438	1579	33	58	65	68
Large	Qtotal	B	10	466	708	902	985	68	113	121	126
Large	Qtotal	B	12	886	1306	1722	1889	66	83	93	96
Large	Qtotal	B	13	802	1209	1609	1769	63	101	131	144
Large	Qtotal	B	16	2215	3334	4484	4935	258	418	625	709
Large	Qtotal	E	1	992	1128	1210	1230	187	274	333	351
Large	Qtotal	E	3	390	434	455	458	155	185	201	203
Large	Qtotal	E	10	292	346	373	381	171	216	239	246
Large	Qtotal	E	12	678	785	850	869	266	338	390	408
Large	Qtotal	E	13	593	685	737	764	281	356	404	432
Large	Qtotal	E	16	2246	2789	2966	3012	980	1385	1552	1597
Large	ASH62.2_2016	B	1	100	159	212	225	-5	-12	-34	-54
Large	ASH62.2_2016	B	3	-21	-37	-44	-50	-24	-46	-63	-74
Large	ASH62.2_2016	B	10	23	34	57	61	32	39	52	50
Large	ASH62.2_2016	B	12	65	97	131	139	55	68	71	65
Large	ASH62.2_2016	B	13	96	153	200	214	113	163	196	201
Large	ASH62.2_2016	B	16	959	1433	1912	2098	524	758	984	1066
Large	ASH62.2_2016	E	1	808	567	330	288	132	252	273	290
Large	ASH62.2_2016	E	3	250	94	-28	-58	75	105	99	95
Large	ASH62.2_2016	E	10	175	156	139	139	197	247	270	278
Large	ASH62.2_2016	E	12	461	414	360	349	301	414	472	486
Large	ASH62.2_2016	E	13	415	367	330	323	391	495	556	571
Large	ASH62.2_2016	E	16	1830	2276	2276	2281	1201	1781	1959	2003
Large	T24_2019	B	1	1702	2518	2571	2584	122	164	142	122
Large	T24_2019	B	3	728	1090	1083	1077	58	89	73	61

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	T24_2019	B	10	462	670	692	697	84	111	124	123
Large	T24_2019	B	12	854	1275	1308	1317	60	86	89	83
Large	T24_2019	B	13	805	1220	1268	1281	78	131	164	169
Large	T24_2019	B	16	2218	3365	3844	4030	297	511	736	818
Large	T24_2019	E	1	1341	1505	1268	1226	324	428	449	466
Large	T24_2019	E	3	497	540	418	389	183	213	207	204
Large	T24_2019	E	10	314	362	344	344	181	221	244	252
Large	T24_2019	E	12	743	862	808	797	273	354	411	426
Large	T24_2019	E	13	642	748	710	703	292	381	443	457
Large	T24_2019	E	16	2289	2918	2917	2923	973	1448	1626	1671
Large	BuilderPractice	B	1	1715	2541	3378	3688	122	168	226	222
Large	BuilderPractice	B	3	723	1074	1466	1589	52	71	132	122
Large	BuilderPractice	B	10	457	669	877	952	81	113	141	142
Large	BuilderPractice	B	12	852	1276	1701	1870	58	83	109	117
Large	BuilderPractice	B	13	810	1221	1620	1763	83	133	174	170
Large	BuilderPractice	B	16	2220	3368	4496	4946	300	517	756	865
Large	BuilderPractice	E	1	1605	1922	2019	2048	243	414	498	532
Large	BuilderPractice	E	3	657	737	753	754	158	217	226	226
Large	BuilderPractice	E	10	368	451	500	507	173	248	303	311
Large	BuilderPractice	E	12	837	1065	1141	1161	230	394	465	488
Large	BuilderPractice	E	13	766	938	1002	1019	282	420	491	514
Large	BuilderPractice	E	16	2314	3286	3577	3635	854	1570	1896	1969
Large	None	B	1	1560	2330	3051	3330	217	396	537	582
Large	None	B	3	650	953	1256	1371	126	180	295	360
Large	None	B	10	372	557	755	805	124	241	670	797
Large	None	B	12	842	1246	1625	1773	177	294	412	492
Large	None	B	13	800	1162	1580	1738	141	117	393	657
Large	None	B	16	2180	3269	4368	4787	154	277	598	697
Large	None	E	1	1560	2330	3051	3330	217	396	537	582
Large	None	E	3	650	953	1256	1371	126	180	295	360
Large	None	E	10	372	557	755	805	124	241	670	797
Large	None	E	12	842	1246	1625	1773	177	294	412	492
Large	None	E	13	800	1162	1580	1738	141	117	393	657

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Large	None	E	16	2180	3269	4368	4787	154	277	598	697
Med	T24_2008	B	1	882	1333	1740	1893	88	155	168	158
Med	T24_2008	B	3	348	535	705	763	18	44	48	33
Med	T24_2008	B	10	197	314	420	453	18	52	76	70
Med	T24_2008	B	12	456	670	892	982	45	50	66	73
Med	T24_2008	B	13	399	599	791	867	28	43	43	40
Med	T24_2008	B	16	1178	1774	2383	2618	210	348	530	601
Med	T24_2008	E	1	701	805	862	873	205	297	353	368
Med	T24_2008	E	3	239	262	276	277	56	75	87	89
Med	T24_2008	E	10	189	217	230	233	150	185	200	204
Med	T24_2008	E	12	414	491	533	542	184	252	297	311
Med	T24_2008	E	13	371	438	465	474	215	288	325	341
Med	T24_2008	E	16	1253	1658	1771	1798	770	1230	1408	1456
Med	T24_2013	B	1	-43	-71	-102	-113	-10	-27	-52	-62
Med	T24_2013	B	3	-75	-108	-135	-146	-47	-67	-82	-90
Med	T24_2013	B	10	3	-7	-17	-20	16	11	3	0
Med	T24_2013	B	12	3	-5	-15	-19	18	12	0	-5
Med	T24_2013	B	13	0	-3	-8	-11	28	35	37	37
Med	T24_2013	B	16	407	613	810	887	258	380	486	525
Med	T24_2013	E	1	78	-258	-645	-811	153	168	144	131
Med	T24_2013	E	3	-52	-235	-416	-488	40	7	-9	-12
Med	T24_2013	E	10	1	-70	-169	-198	123	126	100	104
Med	T24_2013	E	12	83	-48	-211	-279	196	235	249	255
Med	T24_2013	E	13	12	-121	-261	-318	215	252	285	296
Med	T24_2013	E	16	733	553	289	178	1015	1193	1274	1299
Med	Qtotal	B	1	939	1379	1819	1996	74	92	109	117
Med	Qtotal	B	3	375	548	754	833	15	10	32	38
Med	Qtotal	B	10	209	328	451	486	10	28	48	44
Med	Qtotal	B	12	449	668	893	978	16	18	23	19
Med	Qtotal	B	13	422	639	863	940	29	48	75	76
Med	Qtotal	B	16	1169	1745	2325	2557	146	222	307	344
Med	Qtotal	E	1	171	232	262	269	94	129	149	156
Med	Qtotal	E	3	54	65	70	71	31	36	39	40

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Med	Qtotal	E	10	47	58	67	70	34	40	46	50
Med	Qtotal	E	12	129	172	198	202	71	98	119	123
Med	Qtotal	E	13	96	129	153	157	61	89	113	117
Med	Qtotal	E	16	581	686	761	778	399	492	563	580
Med	ASH62.2_2016	B	1	-43	-71	-102	-113	-10	-27	-52	-62
Med	ASH62.2_2016	B	3	-75	-108	-135	-146	-47	-67	-82	-90
Med	ASH62.2_2016	B	10	3	-7	-17	-20	16	11	3	0
Med	ASH62.2_2016	B	12	3	-5	-15	-19	18	12	0	-5
Med	ASH62.2_2016	B	13	0	-3	-8	-11	28	35	37	37
Med	ASH62.2_2016	B	16	407	613	810	887	258	380	486	525
Med	ASH62.2_2016	E	1	-278	-434	-533	-553	153	170	181	187
Med	ASH62.2_2016	E	3	-184	-262	-314	-325	49	50	47	48
Med	ASH62.2_2016	E	10	-29	-58	-67	-68	56	55	61	64
Med	ASH62.2_2016	E	12	-42	-87	-113	-115	132	158	179	188
Med	ASH62.2_2016	E	13	-58	-92	-113	-117	117	149	170	175
Med	ASH62.2_2016	E	16	470	447	440	442	658	768	840	859
Med	T24_2019	B	1	878	1338	1306	1295	51	97	72	62
Med	T24_2019	B	3	382	574	547	536	29	47	32	24
Med	T24_2019	B	10	240	360	350	347	42	66	58	55
Med	T24_2019	B	12	452	682	672	668	24	39	27	21
Med	T24_2019	B	13	443	647	642	639	54	67	69	68
Med	T24_2019	B	16	1162	1755	1952	2029	156	258	364	403
Med	T24_2019	E	1	183	244	145	125	102	137	148	154
Med	T24_2019	E	3	53	63	11	1	30	34	32	32
Med	T24_2019	E	10	29	43	33	32	16	25	32	34
Med	T24_2019	E	12	139	175	149	147	78	98	119	129
Med	T24_2019	E	13	107	138	118	114	71	97	119	124
Med	T24_2019	E	16	623	729	722	724	428	526	598	617
Med	BuilderPractice	B	1	890	1341	1772	1936	62	104	126	126
Med	BuilderPractice	B	3	390	571	745	821	39	48	48	55
Med	BuilderPractice	B	10	242	339	421	482	50	53	38	63
Med	BuilderPractice	B	12	449	673	886	976	24	35	32	36
Med	BuilderPractice	B	13	444	642	840	915	59	67	73	71

Prototype	Fan Sizing Method	Fan Type	Climate Zone	Energy Savings From Airtightening from 5 ACH_{50} (kWh/year)							
				Raw Savings				*Normalized Savings*			
				3	*2*	*1*	*0.6*	*3*	*2*	*1*	*0.6*
Med	BuilderPractice	B	16	1167	1754	2334	2575	169	270	376	432
Med	BuilderPractice	E	1	350	419	457	469	191	241	268	283
Med	BuilderPractice	E	3	112	125	134	134	84	90	96	95
Med	BuilderPractice	E	10	122	143	151	160	109	131	136	148
Med	BuilderPractice	E	12	243	287	325	331	137	167	203	211
Med	BuilderPractice	E	13	192	226	249	256	124	154	181	190
Med	BuilderPractice	E	16	1015	1166	1261	1283	703	866	980	1008
Med	None	B	1	802	1158	1517	1651	218	238	303	203
Med	None	B	3	315	481	626	685	11	54	-47	-168
Med	None	B	10	176	262	327	367	98	193	193	479
Med	None	B	12	412	619	814	891	68	143	197	214
Med	None	B	13	381	575	767	834	28	58	98	-55
Med	None	B	16	1162	1737	2310	2538	133	233	446	626
Med	None	E	1	802	1158	1517	1651	218	238	303	203
Med	None	E	3	315	481	626	685	11	54	-47	-168
Med	None	E	10	176	262	327	367	98	193	193	479
Med	None	E	12	412	619	814	891	68	143	197	214
Med	None	E	13	381	575	767	834	28	58	98	-55
Med	**None**	**E**	**16**	**1162**	**1737**	**2310**	**2538**	**133**	**233**	**446**	**626**

Relative Exposure Plots

Figure 15 Relative exposure in CZ1 (Arcata), by airtightness, prototype, fan type and fan sizing method.

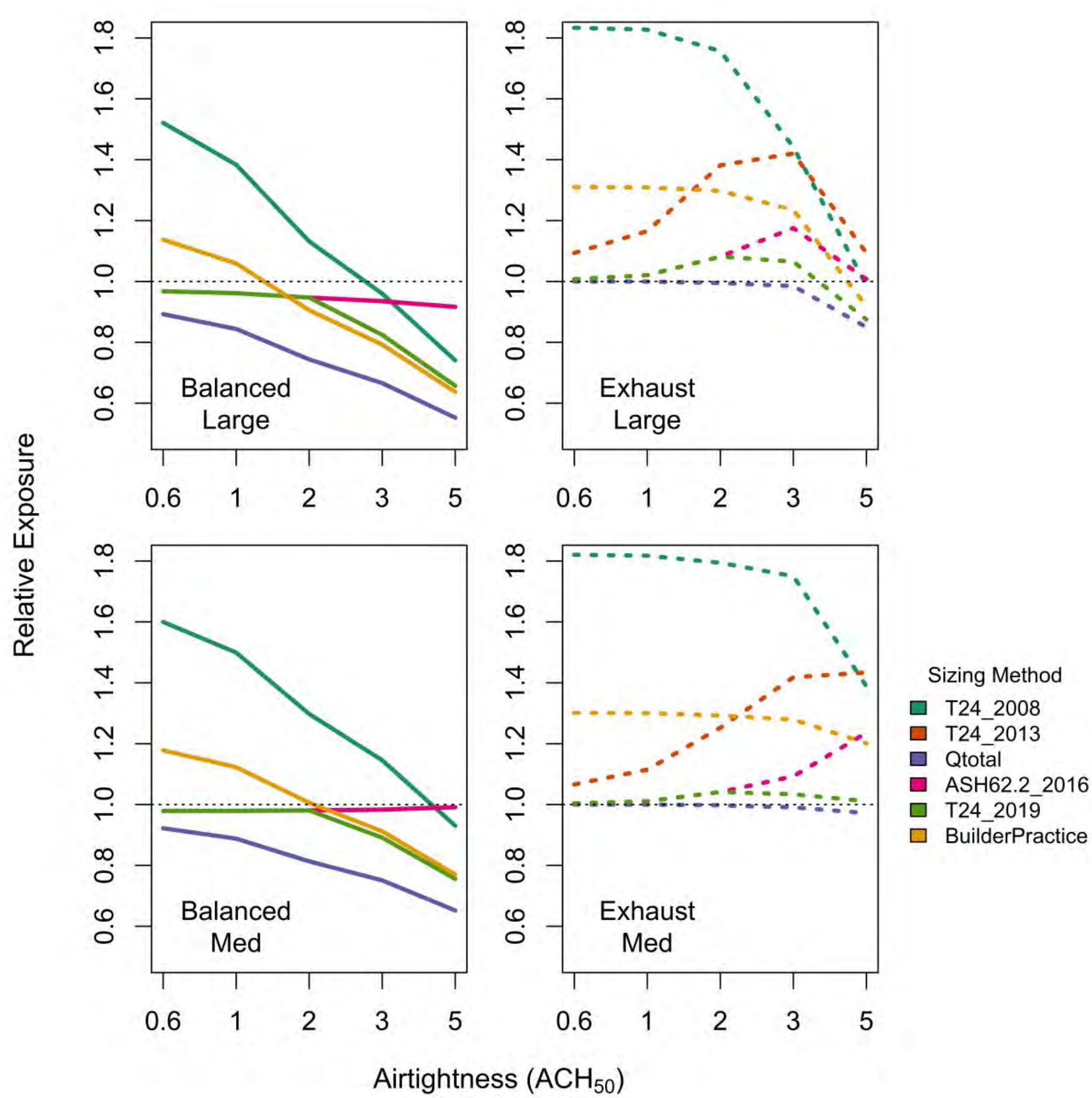


Figure 16 Relative exposure in CZ3 (Oakland), by airtightness, prototype, fan type and fan sizing method.

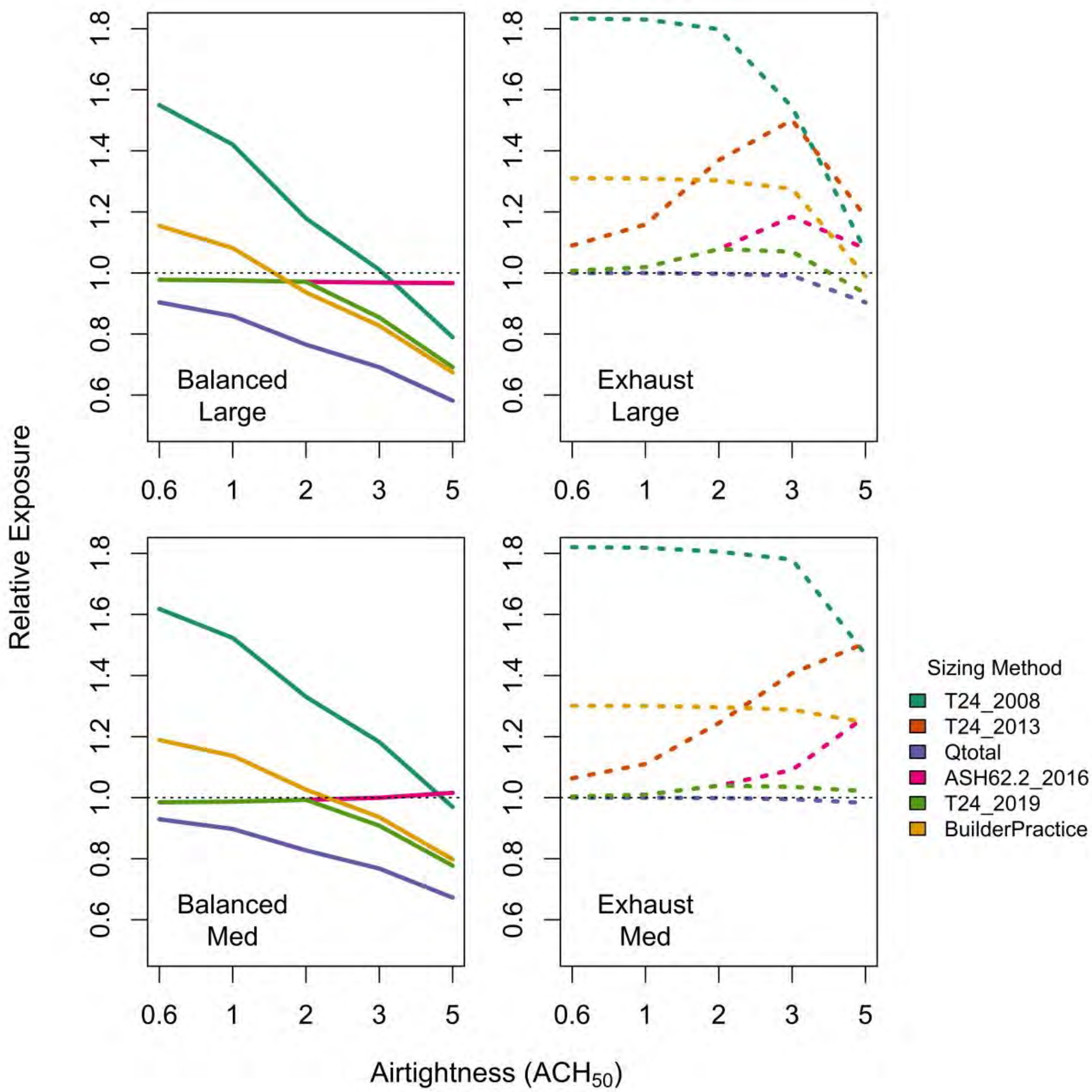


Figure 17 Relative exposure in CZ12 (Sacramento), by airtightness, prototype, fan type and fan sizing method.

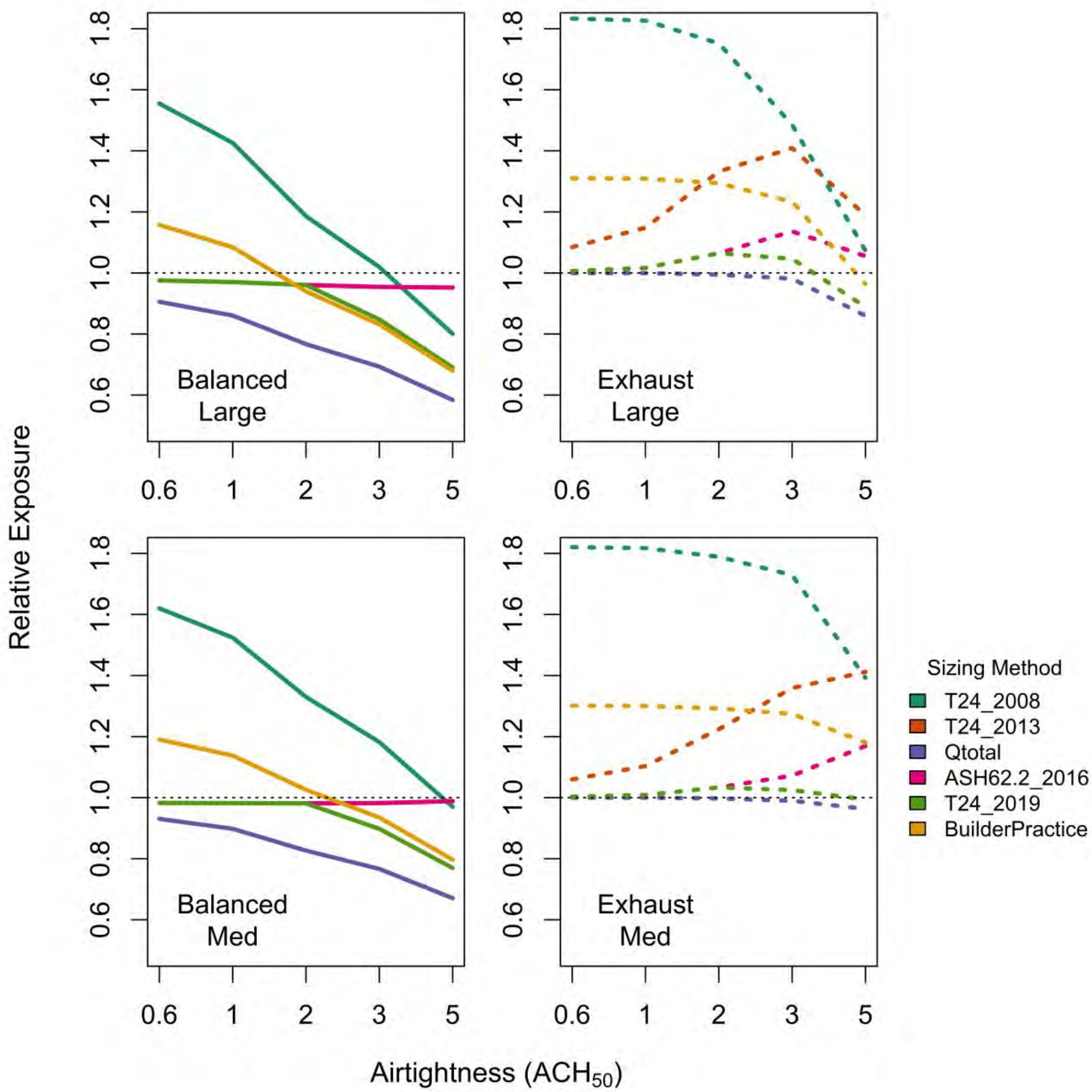


Figure 18 Relative exposure in CZ13 (Fresno), by airtightness, prototype, fan type and fan sizing method.

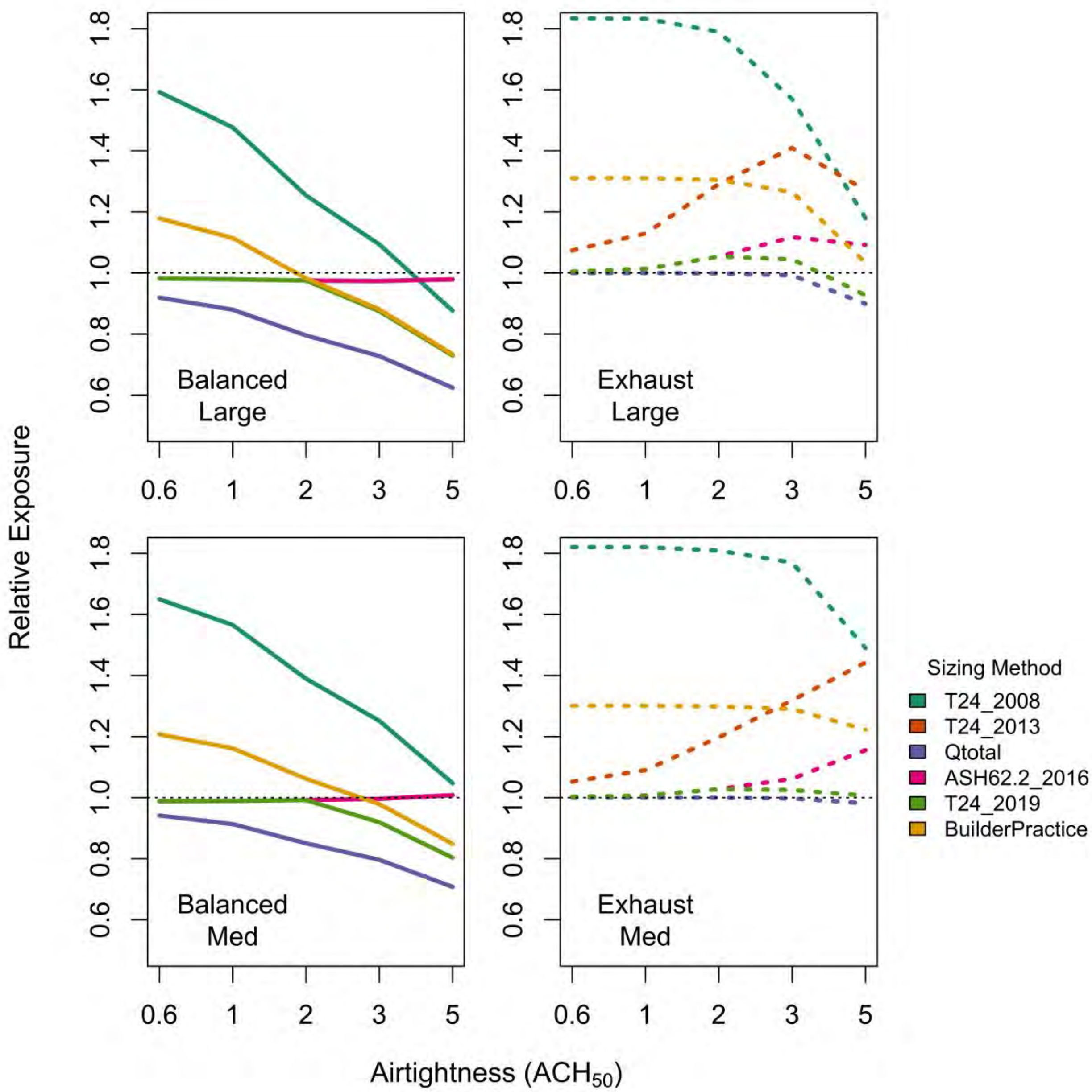
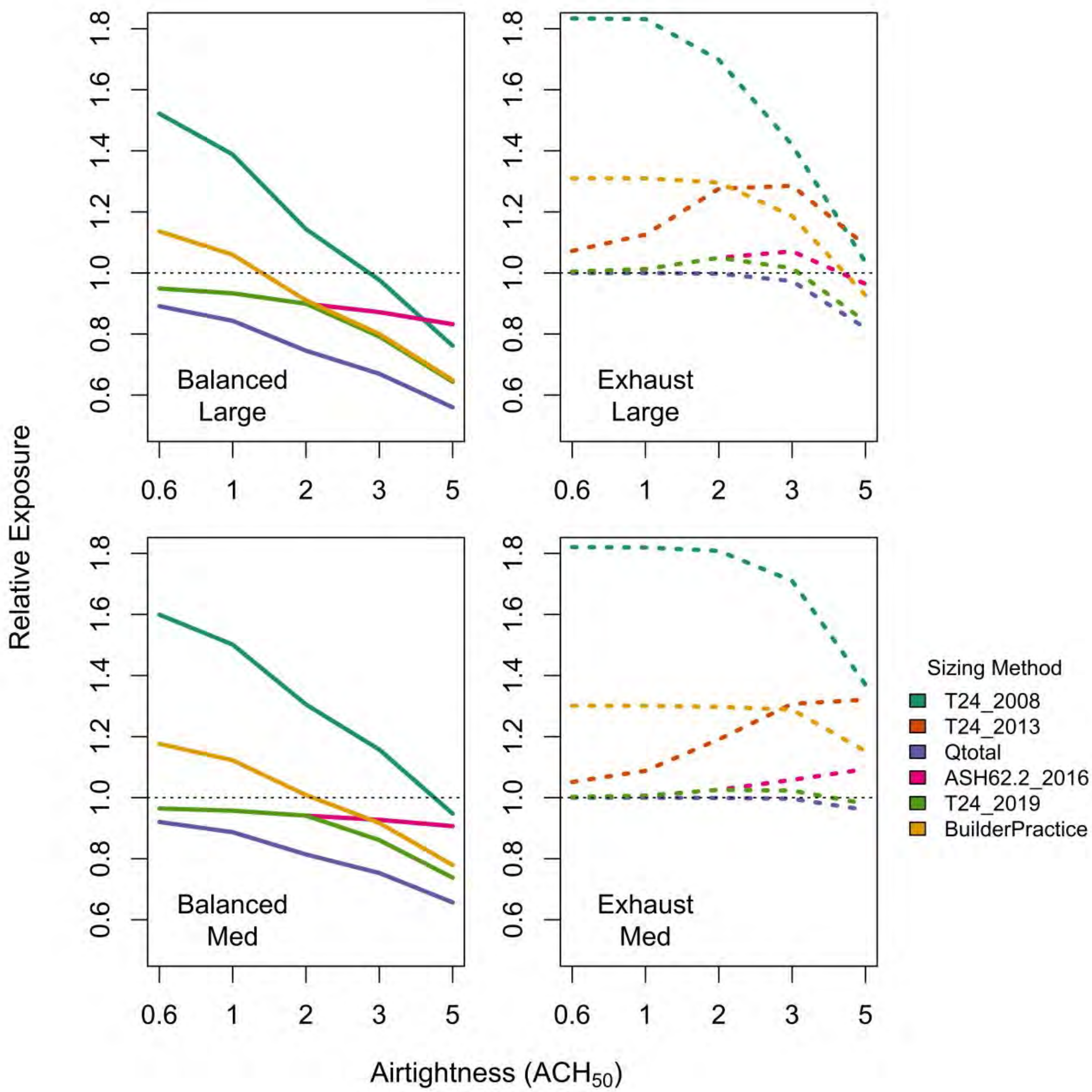


Figure 19 Relative exposure in CZ16 (Blue Canyon), by airtightness, prototype, fan type and fan sizing method.



HVAC Energy Savings from Airtightening Plots

Figure 20 T24_2008 (Fan Ventilation Rate Method) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

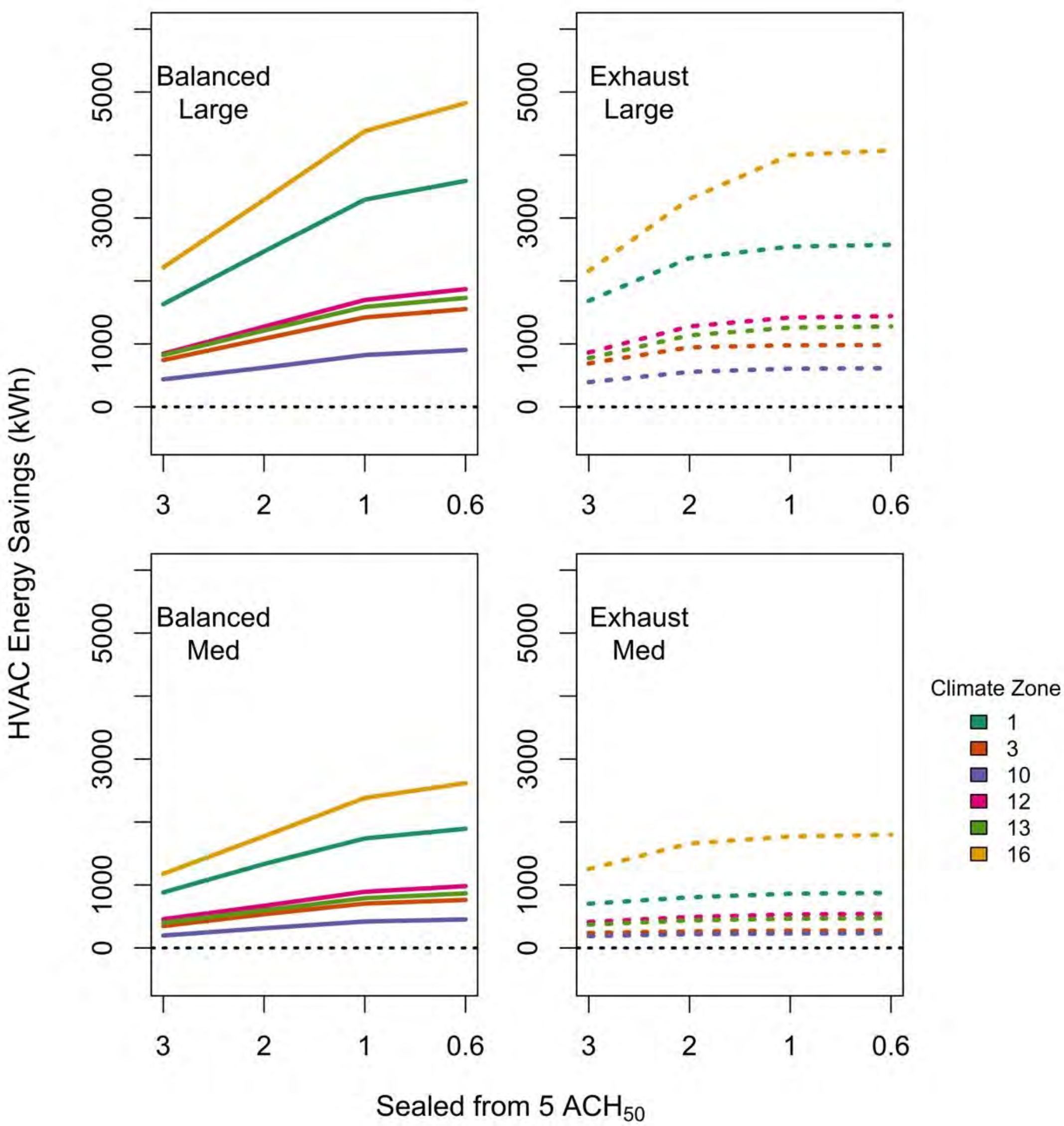


Figure 21 T24_2013 (Total Ventilation Rate Method) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

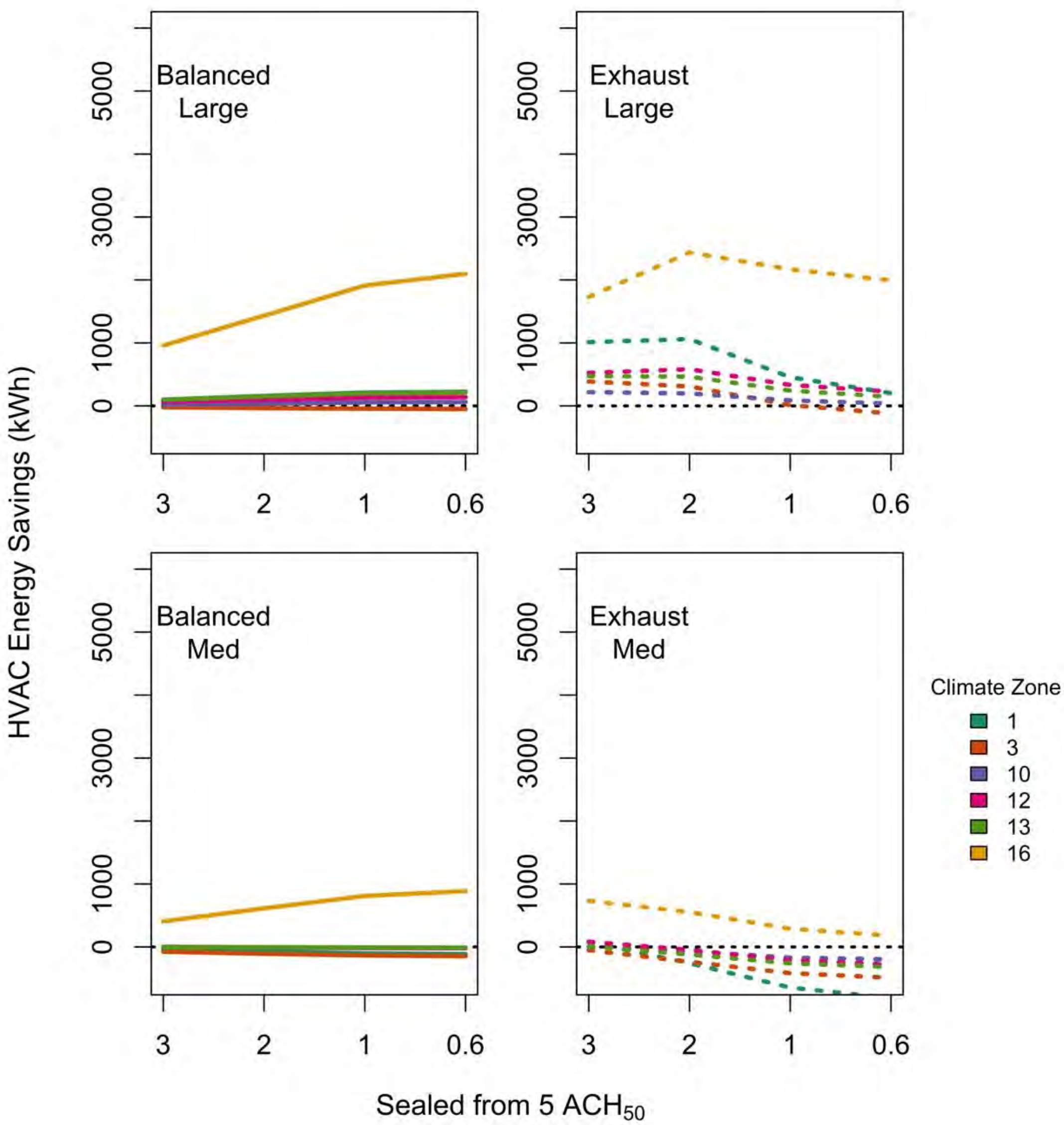


Figure 22 Qtotal cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

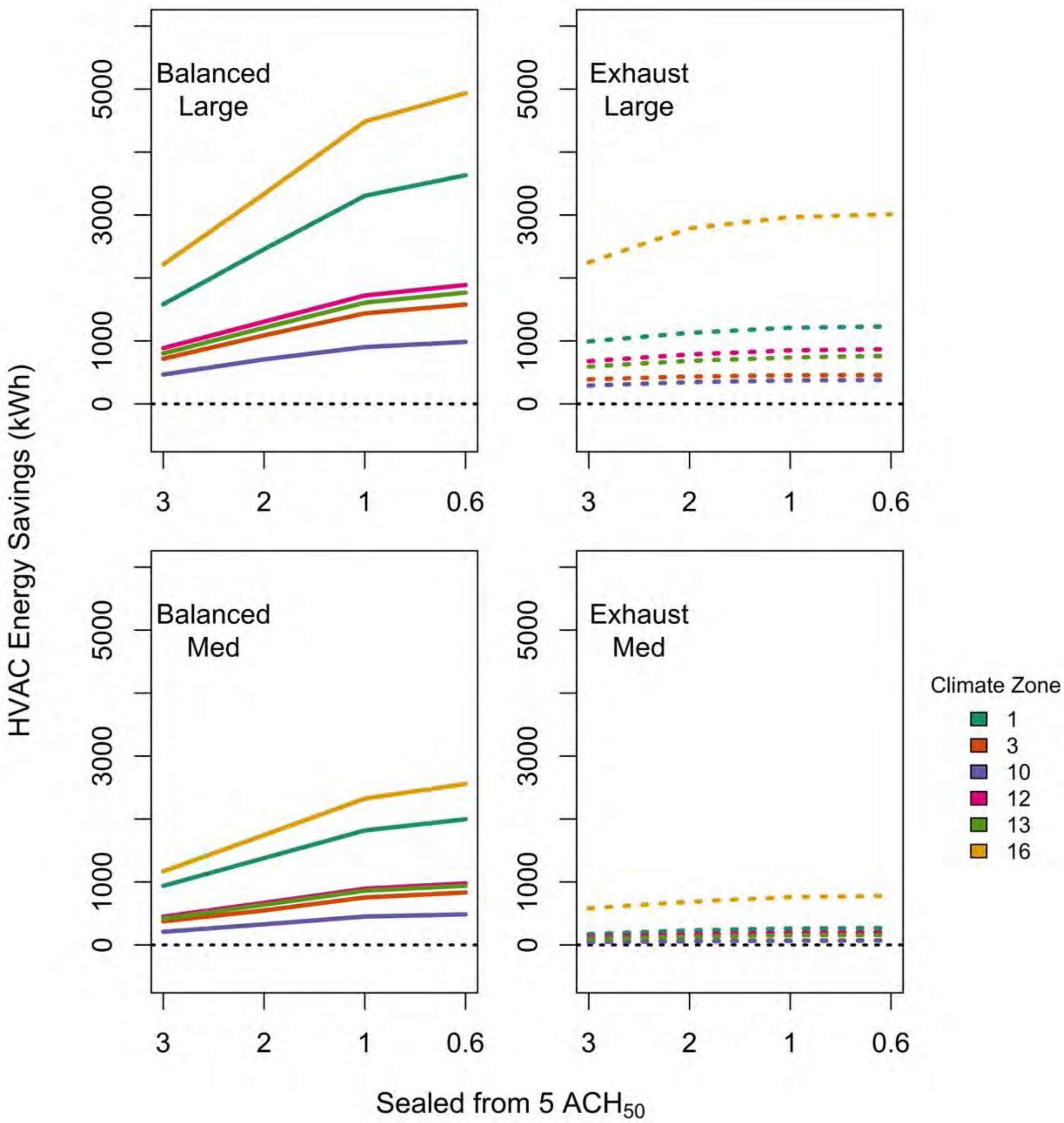
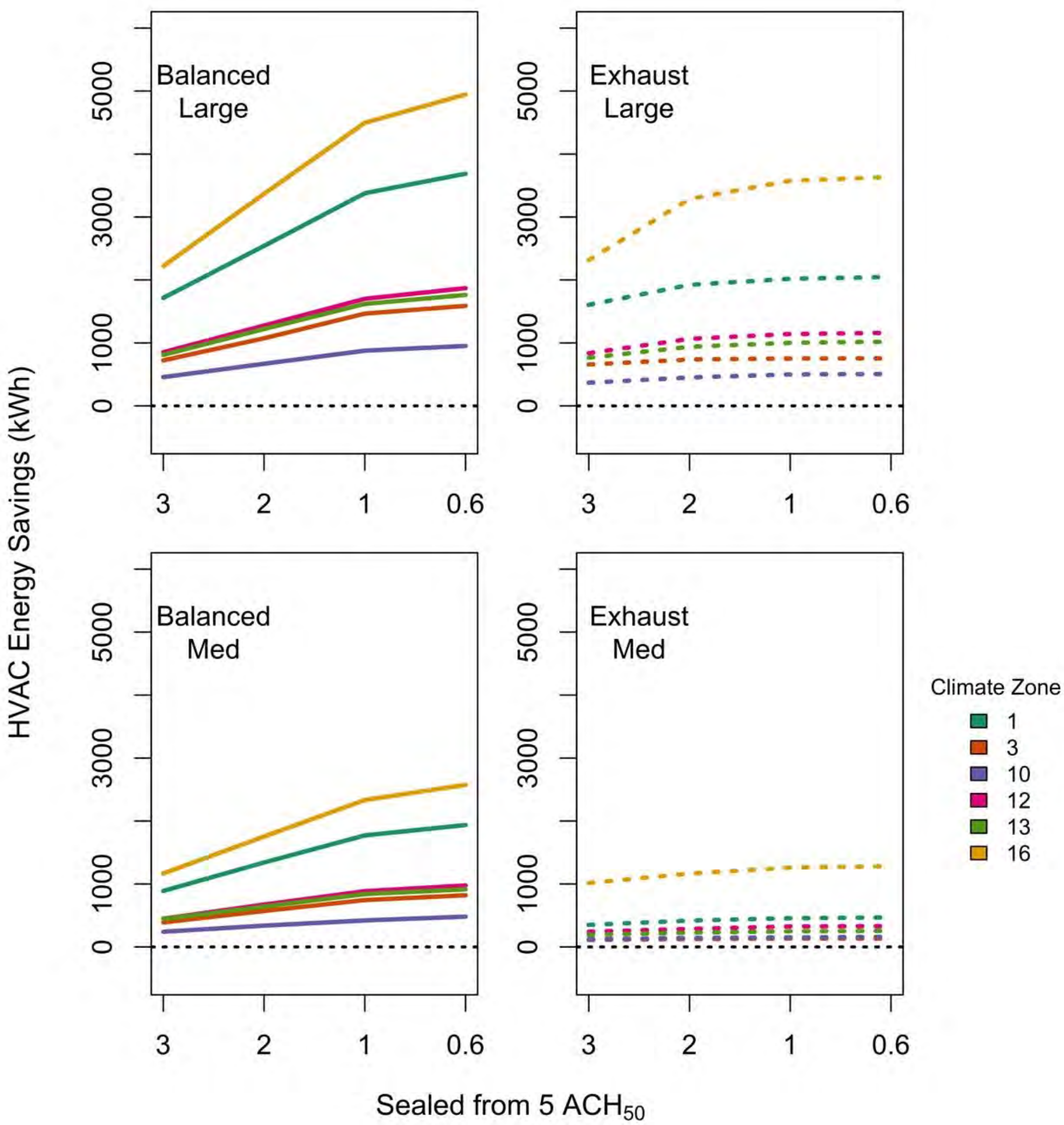


Figure 23 BuilderPractice (40% over-sizing relative to T24_2008) cases, total HVAC energy savings when sealing building envelope from 5 ACH_{50}.



Normalized HVAC Energy Savings from Airtightening Plots

Figure 24 BuilderPractice. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

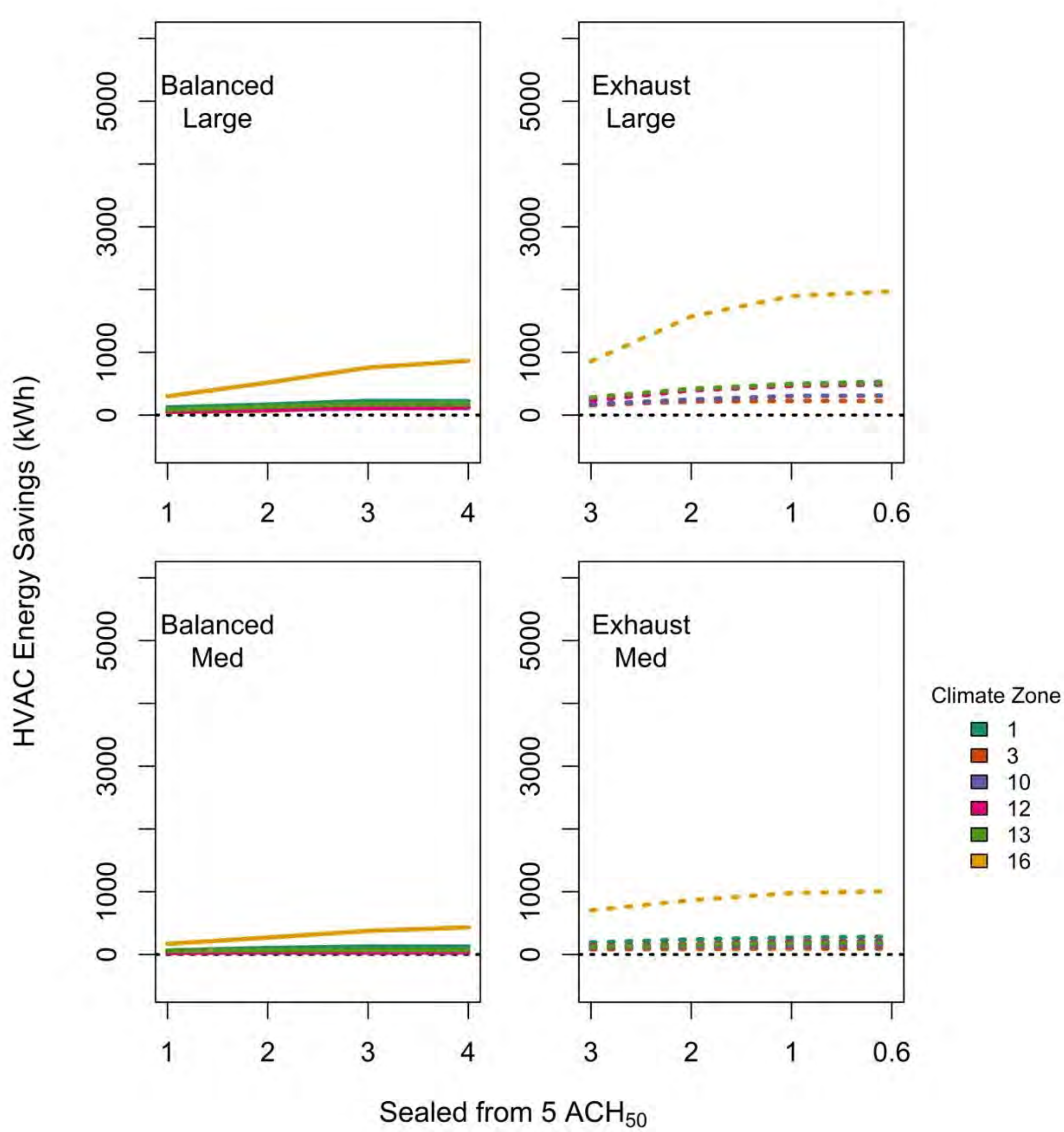


Figure 25 Qtotal. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

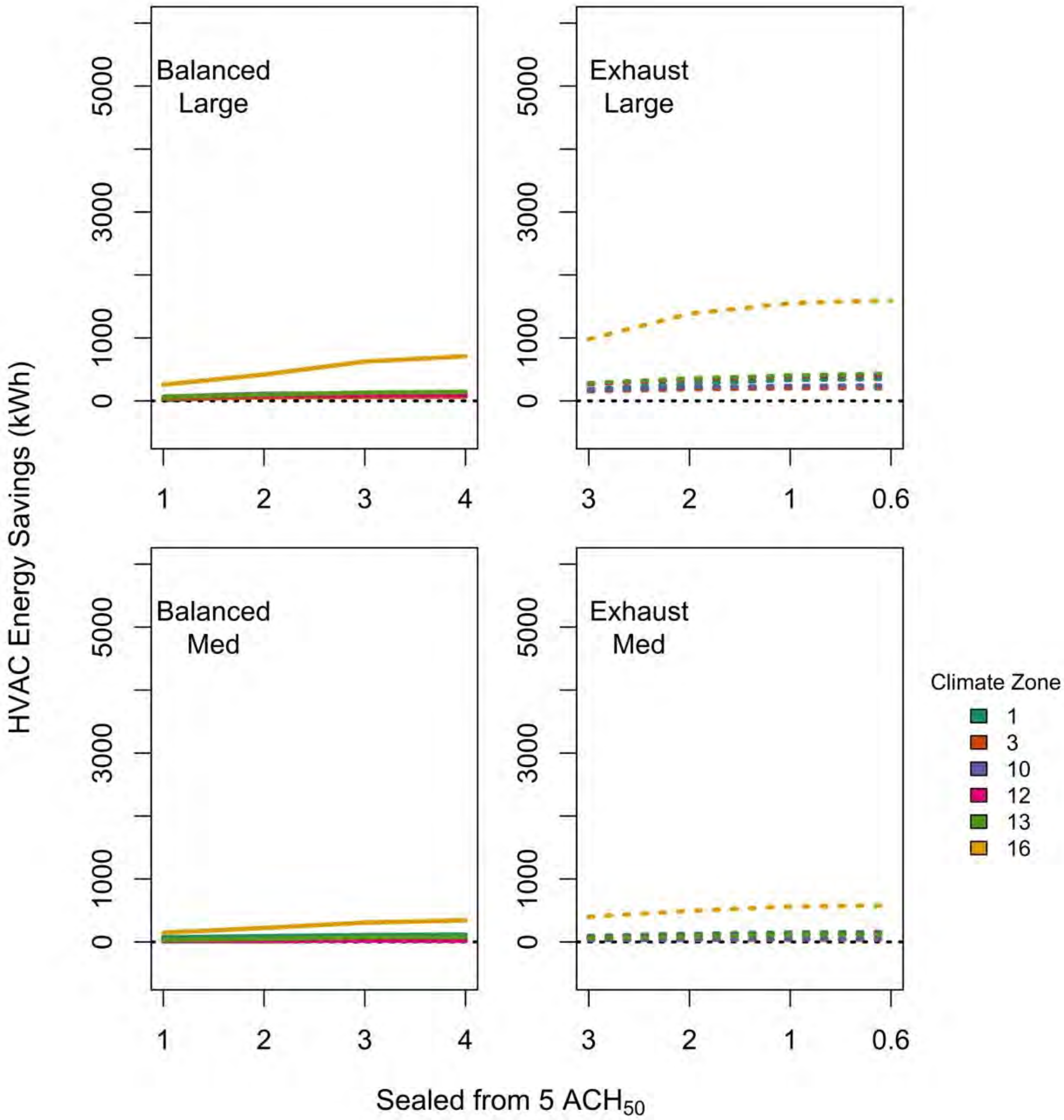


Figure 26 T24_2008. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

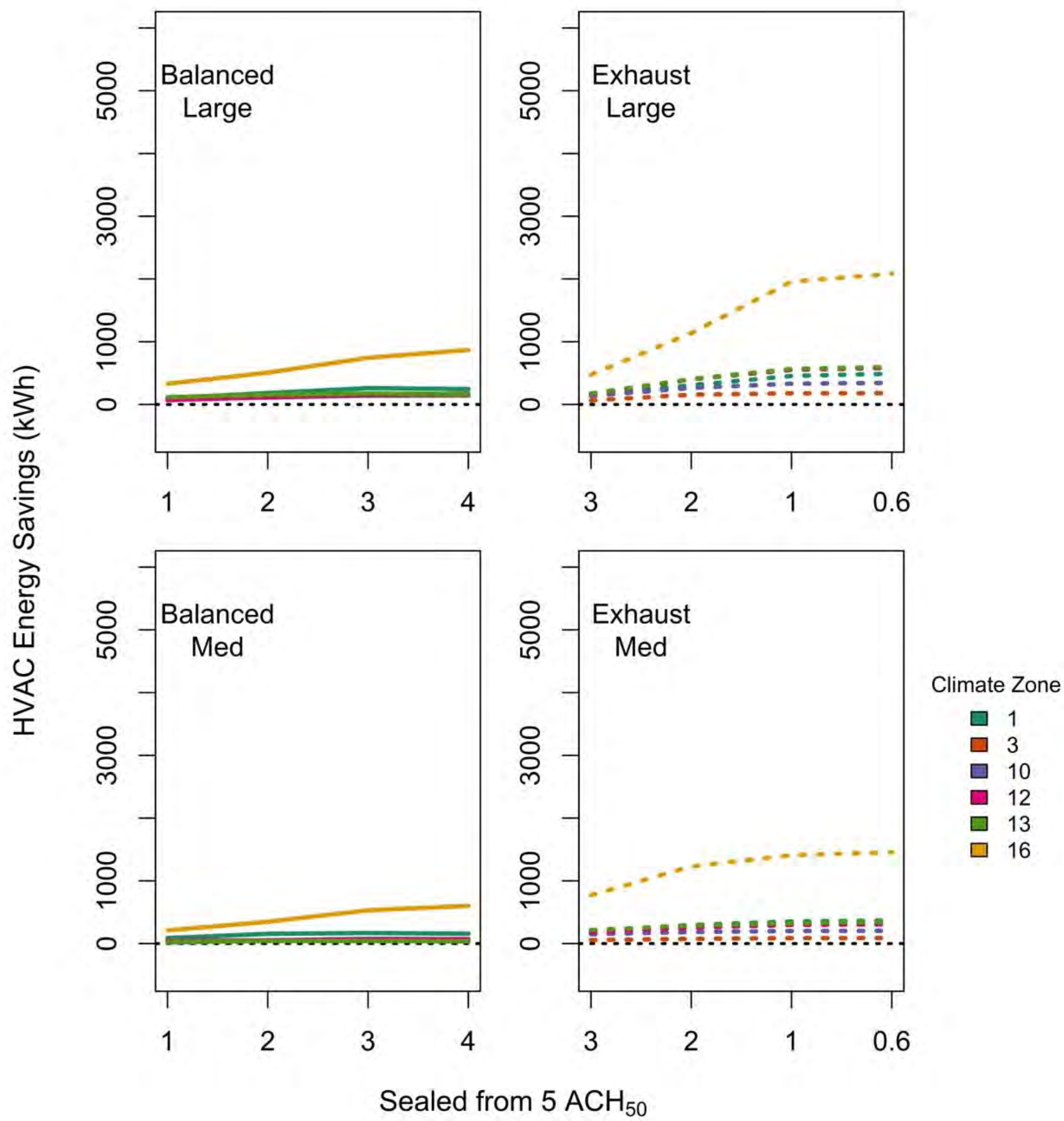
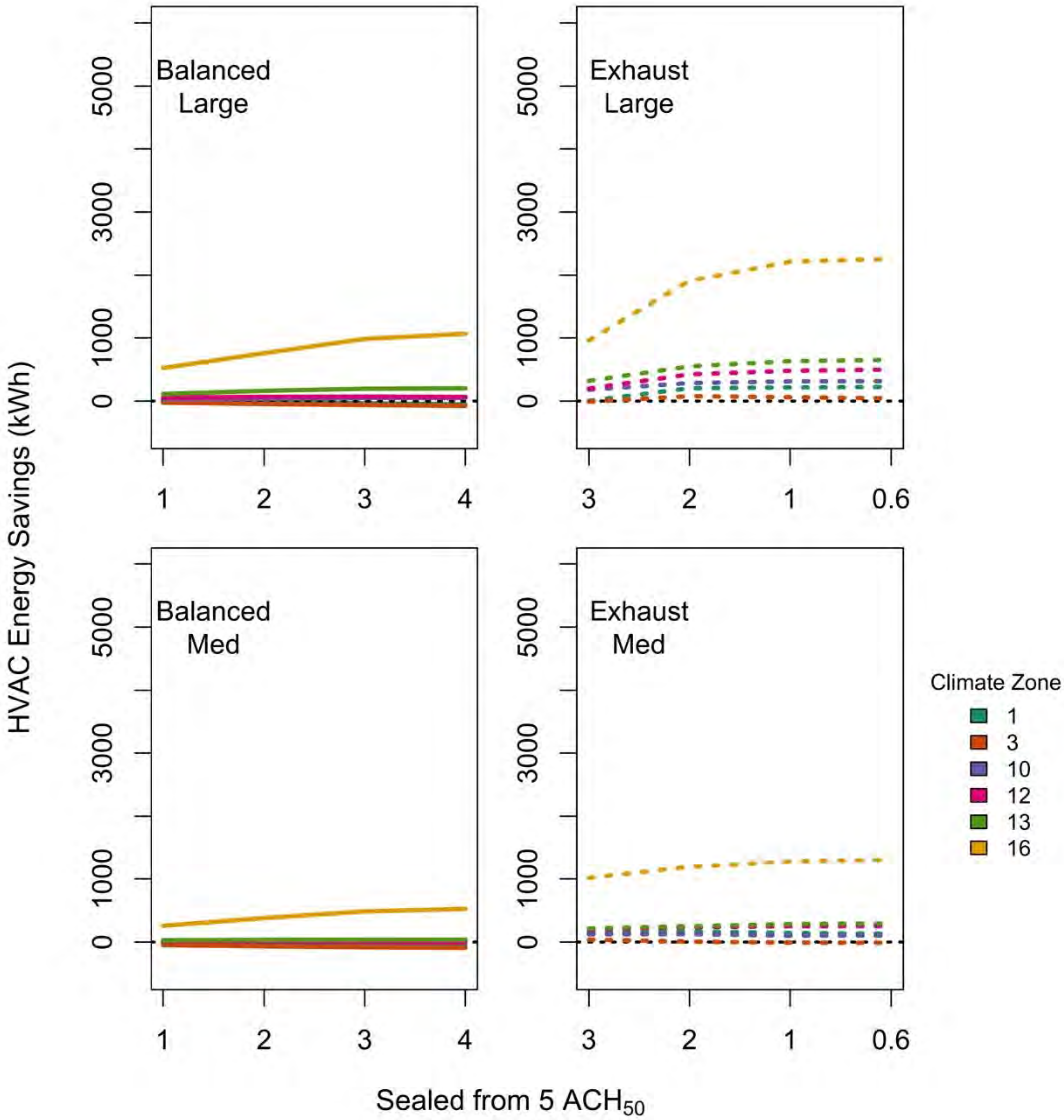


Figure 27 T24_2013. Normalized total HVAC energy savings when sealing building envelope from 5 ACH_{50}.

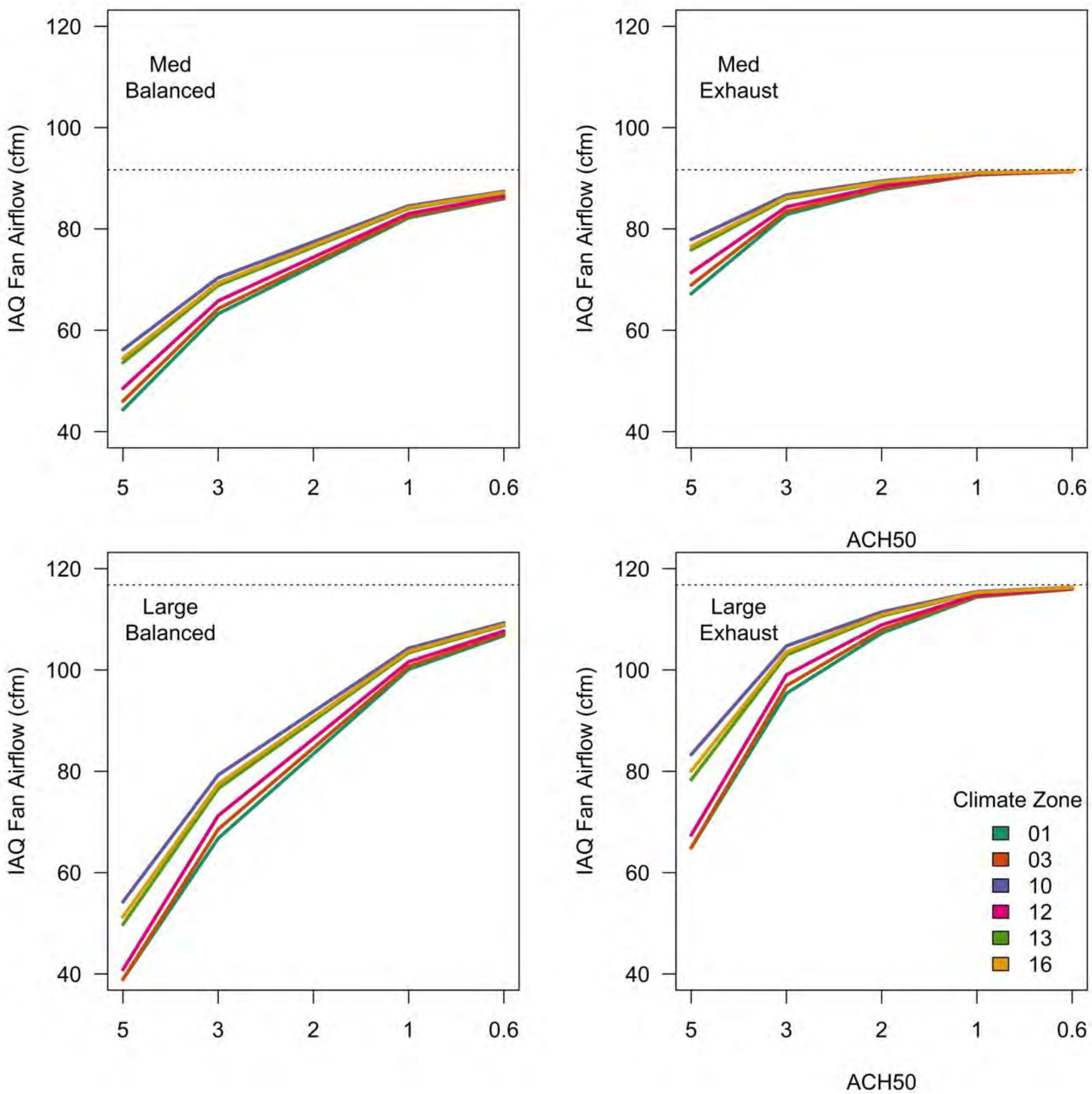


Whole house fan Airflows Illustration Plots

As outlined in Section 3.4, various methods have been or will be available to designers in complying with the IAQ requirements of Title 24. We simulated prototype homes with Whole house fans sized to each of the methods listed in Table 9 and described in Sections 3.4.1 and 3.4.2. We detail below how the ASH622_2016 (Figure 28), T24_2008 (Figure 29) and T24_2019 (Figure 30) sizing methods work in practice by discussing examples of calculated Whole house fan airflows for all prototypes, airtightness levels and climate zones. We selected these example methods, because they illustrate some of the key ways in which the methods differ, namely in how they treat infiltration, Whole house fan type and envelope airtightness. Where relevant, we highlight similarities between the plotted fan sizes and those for related sizing methods (e.g., T24_2008 and BuilderPractice). All other sizing methods not directly discussed are plotted for reference in Figure 31 through Figure 33.

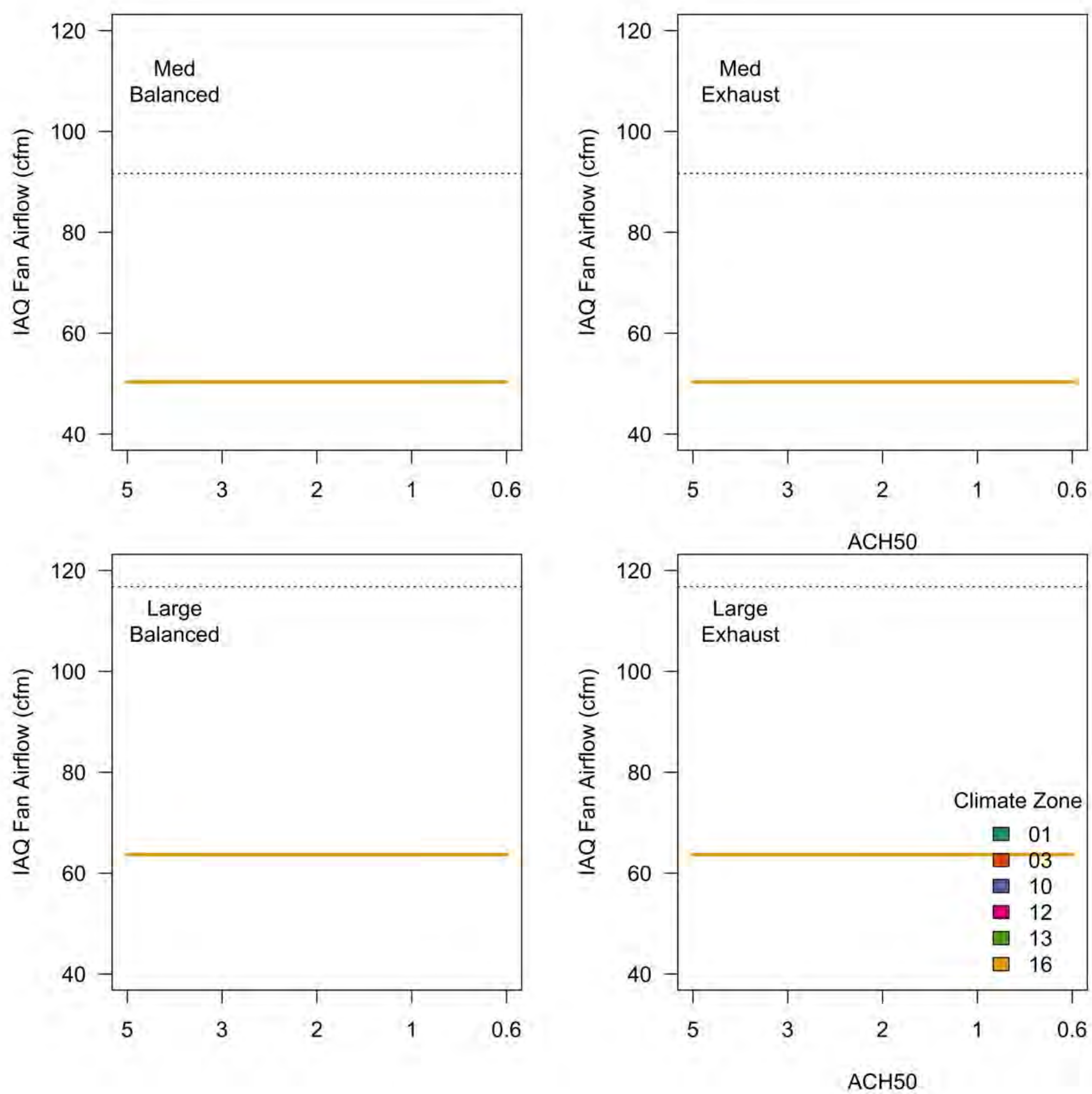
In Figure 28, we show the calculated Whole house fan airflows for each case used in the ASH622_2016 sizing method, which includes the most sophisticated infiltration estimates in fan sizing. The one-story prototypes ("Med") are in the two top panels, and the two-story prototypes ("Large") are in the lower two panels. The panels are separated left-to-right as Balanced or Exhaust fans. Each climate zone is represented by a colored line as indicated in the figure legend. For all cases, the required fan airflow increases as airtightness increase from 5 to 0.6 ACH_{50}. This compensates for reductions in natural infiltration. Differences in fan airflow are greatest between climate zones for the most leaky homes, and all climate zones get the same sized fan as airtightness increases to 0.6 ACH_{50}. Balanced fans change their airflow requirements more rapidly than exhaust fans do, because this sizing method also includes a superposition adjustment, which reduces the airflow credit for infiltration when using an unbalanced fan.

Figure 28 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to ASHRAE 62.2-2016. Grey dotted line shows target ventilation rate (Q_{total}).



In Figure 29, we show the fixed airflow approach of the T24_2008 sizing method, which does not account for natural infiltration in fan sizing. This method only distinguishes between the prototype homes, based on their size. The prescribed airflows are otherwise fixed across fan types, climate zone and airtightness. The BuilderPractice plot would look similar, except the yellow lines would be 40% higher.

Figure 29 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2008. Grey dotted line shows target ventilation rate (Q_{total}).



In Figure 30, we show the required fan airflows when using the T24_2019 sizing method, which includes a fixed infiltration adjustment based on a 2 ACH_{50} envelope and a sub-additivity adjustment for unbalanced fans. The infiltration credit varies by climate zone and house prototype, but not by airtightness, hence the scattered horizontal lines across the airtightness levels. Nevertheless, fan sizes are quite similar across climate zones, varying at most 10 cfm. The superposition adjustment for the unbalanced fans can be seen by comparing the Balanced and Exhaust airflows for the same prototype (i.e., top two panels or lower two panels). The sub-additivity adjustment is greater in the larger, two-story prototype, due to increased infiltration in 2-story homes.

Figure 30 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2019. Grey dotted line shows target ventilation rate (Q_{total}).

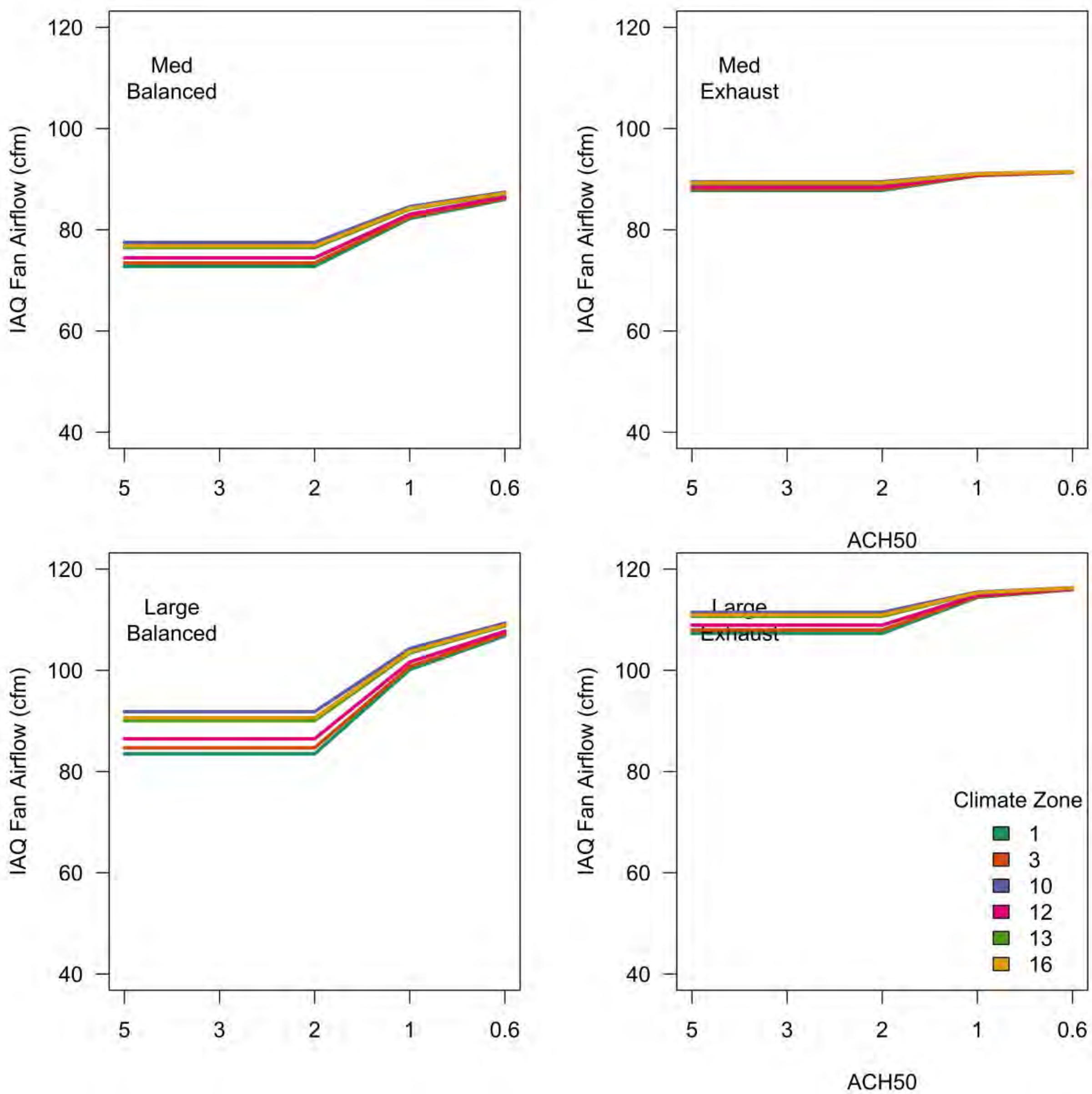


Figure 31 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to T24_2013 method. Grey dotted line shows target ventilation rate (Q_{total}).

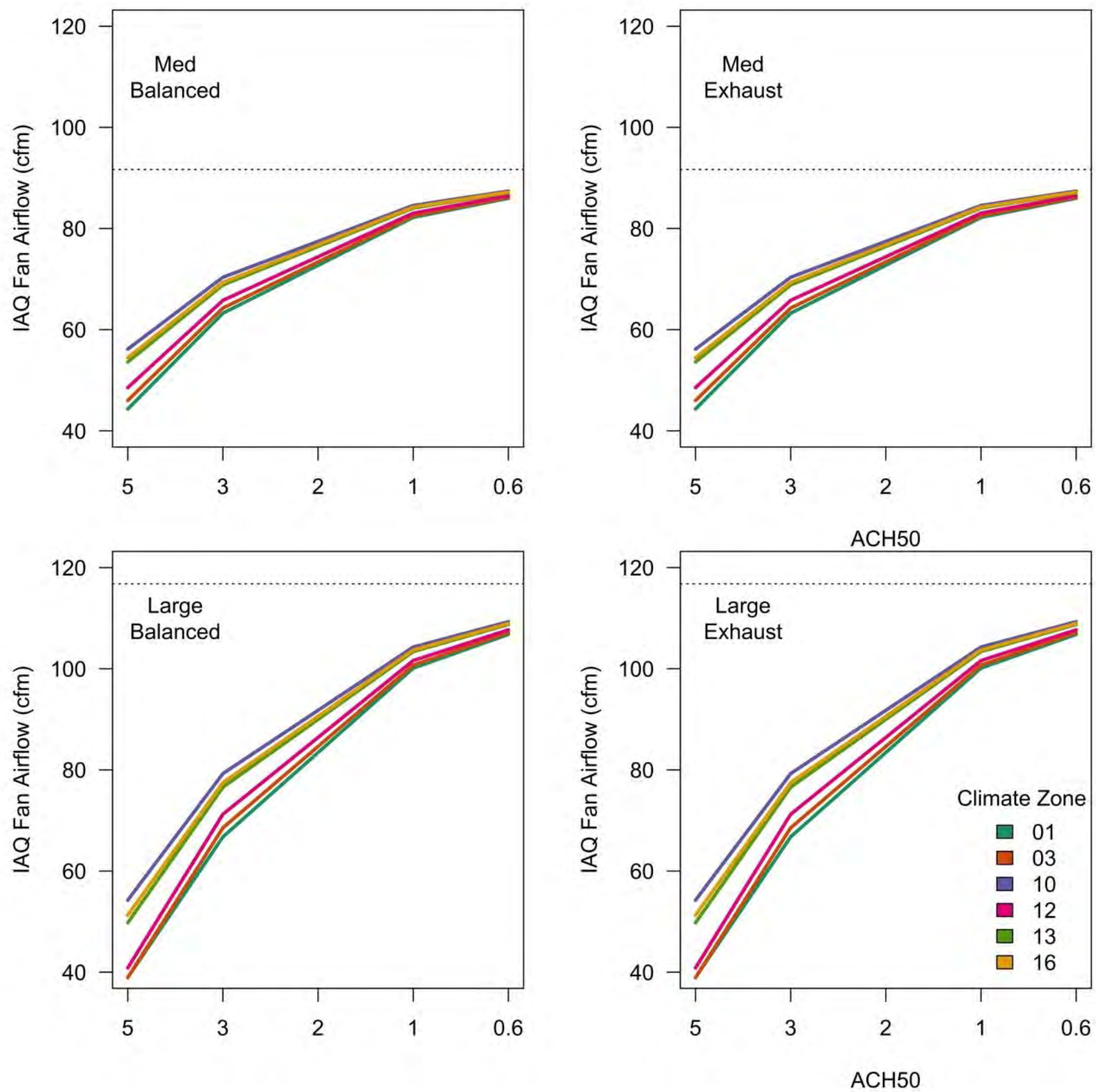


Figure 32 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to BuilderPractice method. Grey dotted line shows target ventilation rate (Q_{total}).

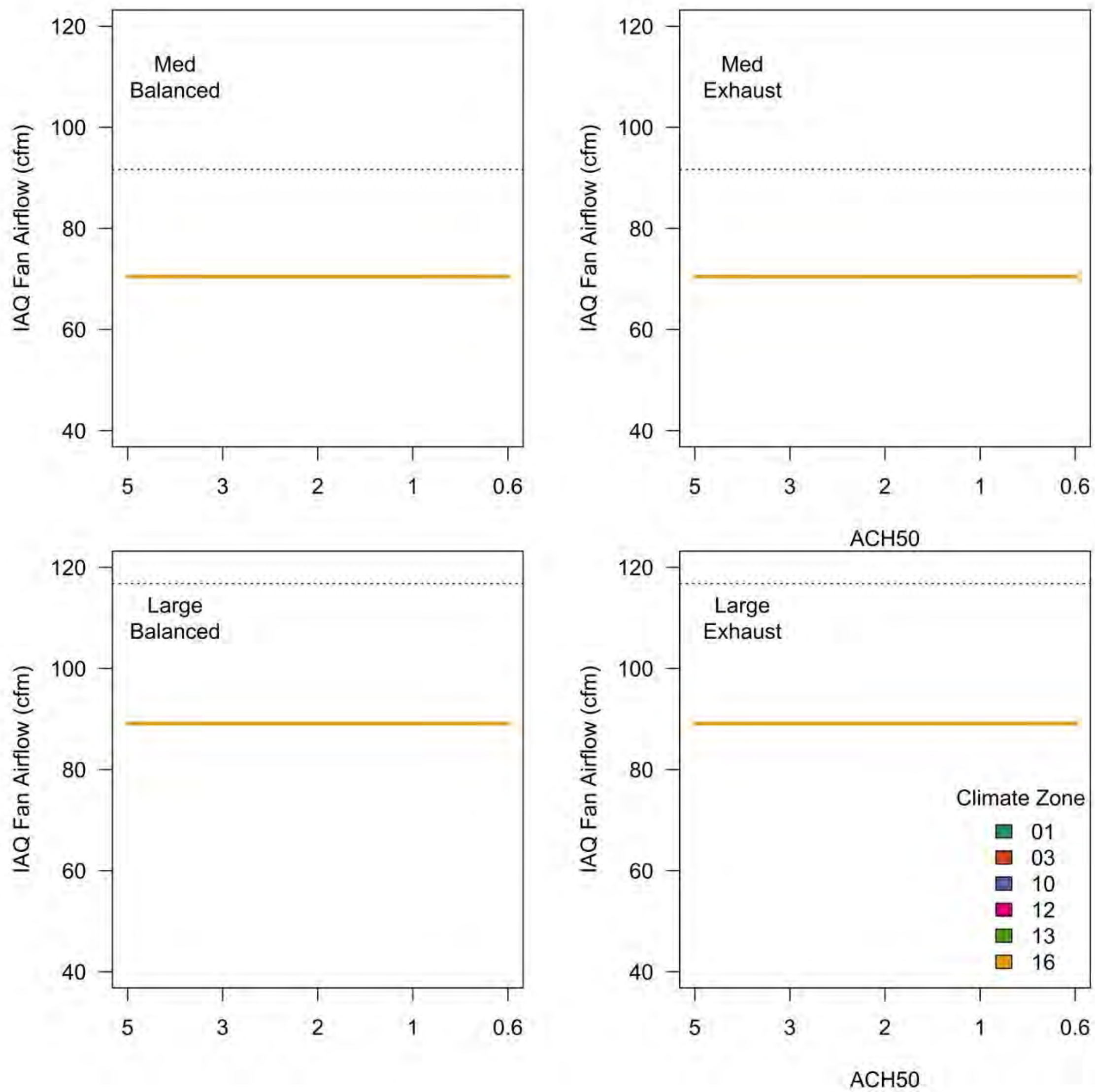
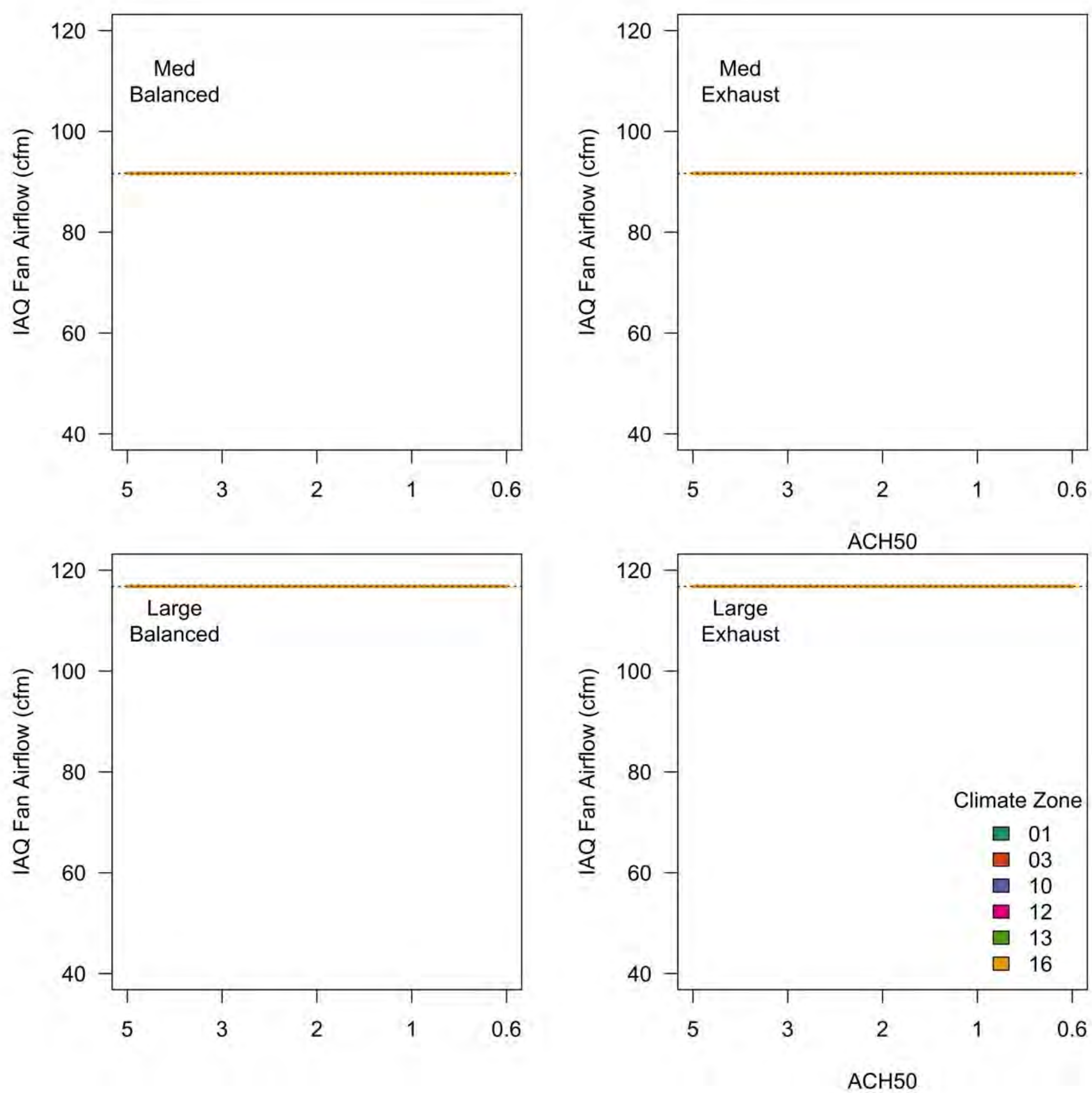


Figure 33 Whole House fan (IAQ fan) airflows for each prototype by airtightness and climate zone. Fan sized to Qtotal method. Grey dotted line shows target ventilation rate (Q_{total}).



Discussion of Infiltration and Sub-Additivity in ASHRAE 62.2-2016 and REGCAP

As noted in the Methods sections of this report, the ASHRAE 62.2-2016 ventilation standard is carefully structured in an effort to help ensure that all compliant homes have similar whole house airflows that are consistent with the target airflow set by the standard (Q_{tot}). Consistent with this, our initial expectation was that the estimated annual average relative exposure for simulations using the ASH622_2016 sizing method would average very close to 1.0 and be tightly clustered around the mean. As shown in the weighted average and individual case sections of this work, while the ASH622_2016 method provided the least variable exposure of all the sizing methods, it still varied from roughly 0.8 to 1.2, with a weighted average of 1.1. This means that by design, some homes would be over- or under-vented by roughly 20%, and on average they would be under-vented by 10%, relative to the target ventilation rate in ASHRAE 62.2 and Title 24.

We hypothesized that the predictions of natural infiltration were higher in the fan sizing calculations than in the REGCAP simulations. This would lead to effectively under-sized Whole house fans, which result in overall higher exposure in the REGCAP model (e.g., mean of 1.1, rather than 1.0). For Whole house fan sizing, the house leakage area derived from blower door testing (i.e., ELA) is combined with the weather and shielding factor (wsf) to estimate the effective annual average infiltration airflow from weather effects. The wsf used in ASHRAE 62.2-2016 fan sizing were derived for each TMY3 location in the United States as described in Turner, Sherman, & Walker (2012). These wsf factors were calculated using certain assumptions about house leakage distributions (i.e., proportion of house leaks in floor, walls and ceiling), as well as TMY3 weather files. They used the AIM-2 advanced infiltration model to estimate infiltration airflows. These wsf are intended to be widely applicable and generic enough to function reasonably across the U.S. housing stock.

Assuming that these infiltration estimates were the cause of high exposure, we examined factors influencing infiltration predictions, each in isolation—weather data (page 107), house leakage distribution (page 109), weather and shielding factors (*wsf*) used in fan sizing (page 109), and superposition of unbalanced fans with infiltration (Section 4.3). We found that overall the simplified infiltration estimates from the ASHRAE standard align reasonably well with those in the REGCAP simulations when no Whole house fan is simulated, but the interaction of mechanical and natural airflows (i.e., superposition/sub-additivity) diverges sharply, leading to the increased weighted average exposure in this paper. This divergence is driven by known biases in the ASHRAE 62.2-2016 sub-additivity model, along with differences in leakage distribution, and to a much lesser extent by the marginal differences in weather data and natural infiltration predictions.

Weather Data

The weather files used in estimating infiltration and sizing the Whole house fan are not the same as those used for demonstrating Title 24 compliance. Weather data is factored into Whole house fan sizing using the weather and shielding factors (wsf), which are based on very geographically granular TMY3 weather data files. These are files commonly used in most building simulation tools and for many assessments of building performance. The California Title 24 uses different weather files entirely for demonstrating compliance based on a fixed energy budget for that geographic climate region. The sixteen CEC climate zones each represent much larger and more variable areas of land and weather than do TMY3 locations. Our understanding is that the outdoor dry-bulb data in the CEC files are adjusted such that the mean and extremes are in-line with reliable weather stations within the climate zone, and that non-dry-bulb data are matched to a single, representative location within the climate zone. Sometimes these generalized climate zone weather data files can differ substantially from TMY3 data used for wsf factors in ASHRAE 62.2-2016. As the determinants of weather induced infiltration in buildings, we examined outdoor dry-bulb temperature and wind speed.

In CEC weather files, the representative city for CZ16 is Blue Canyon, which is located in the Western foothills of the Sierra Nevada mountains at roughly 4,700 ft elevation. For Title 24 compliance, this weather is used to represent nearly the entire Sierra Nevada range in California, including some more harsh and cold locations, such as South Lake Tahoe at 6,200 ft. As such, the TMY3 location for Blue Canyon, CA (TMY3 ID 725845) differs substantially from the CEC CZ16 weather data. See Table 8 for our mapping of CEC climate zones to TMY3 locations. The annual distributions of outdoor dry-bulb temperature are plotted in Figure 34, and the distributions have very similar averages (vertical dashed lines), but the CEC weather data has many more hours in the 0-10°C temperature bin and many fewer hours in the 10 to 20°C bin. This shift affects infiltration due to stack effect based on indoor-outdoor temperature difference, and we expect more stack infiltration when using CEC weather data compared with TMY3 data. This is one of the worst discrepancies between the temperatures in the weather file types, while some others are a quite well-matched.

Wind speed is the other main determinant of weather-induced infiltration in homes, and we see similar differences between weather file types. An example of wind speed distributions is plotted for CZ5 in Figure 35 (Santa Maria, CA, TMY3 ID 723940). The CEC weather data has many more hours in the 0-1 m/s wind speed bin, while having many fewer hours in the roughly 2-4 m/s bin. We expect this to reduce wind-induced infiltration predictions when using CEC weather data, relative to TMY3 data.

Figure 34 Outdoor dry-bulb temperature distributions for Blue Canyon (CZ16), TMY3 versus CEC weather data.

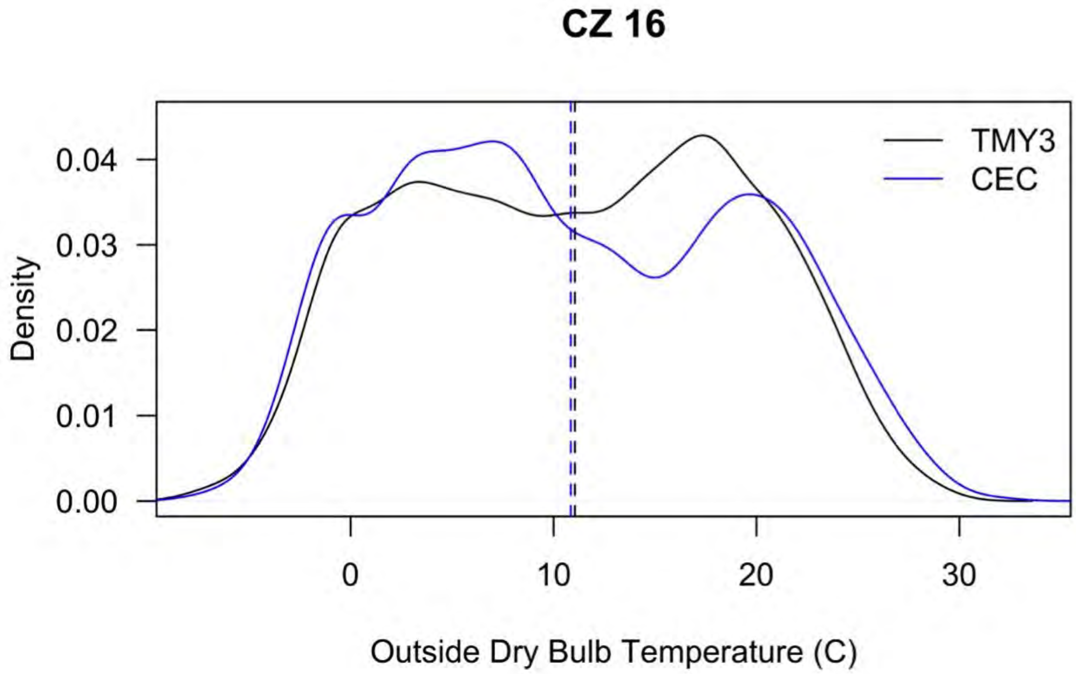
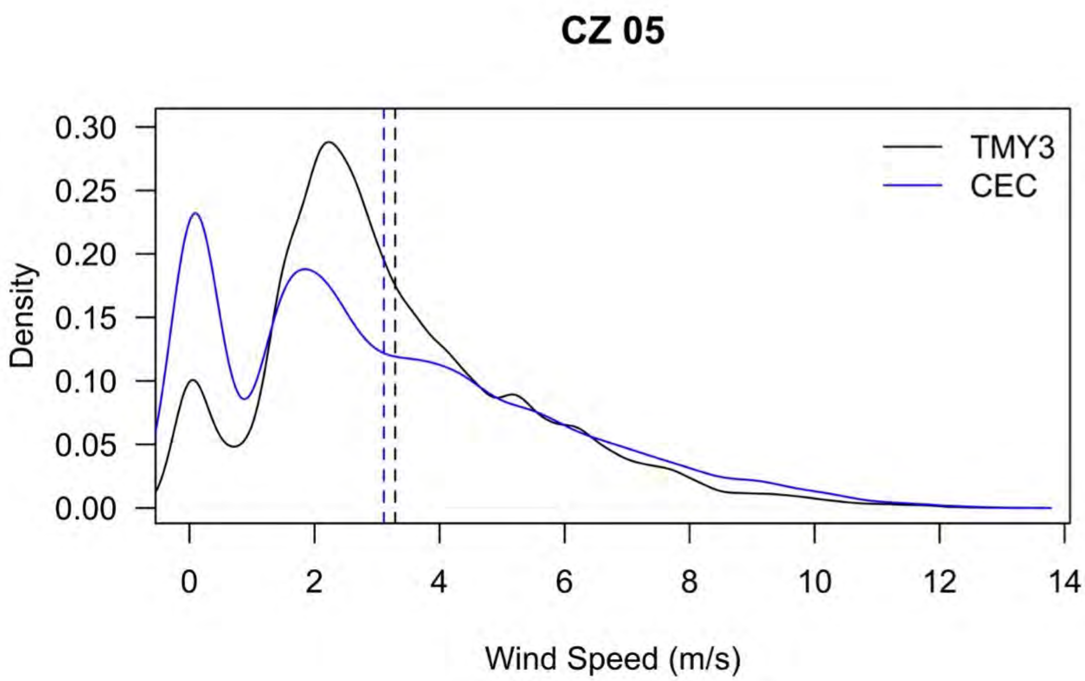


Figure 35 Wind speed distributions for Santa Maria (CZ5), TMY3 versus CEC weather data.



Building Leakage Distribution

The distribution of leakage area across the building envelope, by orientation and height, has a substantial impact on predicted infiltration rates. Per Table 3 in the 2016 Alternative Calculation Method (ACM), Title 24 assumes that 50% of building leaks at in the home's ceiling, between the house and attic volumes. The remaining leaks are distributed between the floor and walls (if crawlspace or basement foundations) or just the walls (slab on grade). This assumption places a lot of leakage area in the ceiling, which is the highest point in the home. The estimate that 50% of leakage is in the ceiling was derived from field measurements in new California homes (Proctor et al., 2011). If this leakage distribution is actually representative of new homes in California, it differs substantially from assumptions for the housing stock elsewhere, and it certainly differs substantially from the assumptions used to generate the 62.2 wsf factors (reproduced from Turner et al. in Table 16 alongside T24 ACM assumptions). The wsf factor analysis assigned between 17 and 25% of total leakage to the ceiling, which is at most half the Title 24 assumption. These differences in leakage distribution can substantially impact the weather-induced infiltration airflow for a residence.

Table 16 Reproduced leakage distribution assumptions used in wsf factor derivations, compared with T24 ACM assumptions.

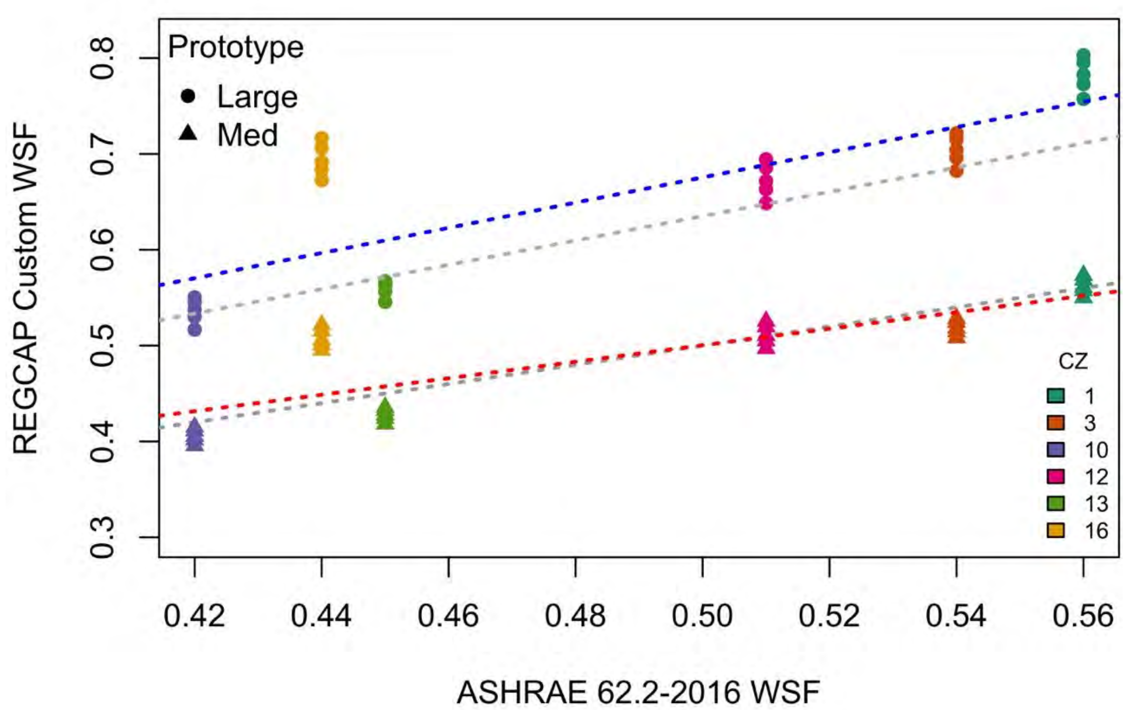
Building Element	Fraction of Total Leakage		
	Turner et al. WSF Analysis		T24 ACM
	1-story	2-story	1- and 2-story
Walls	0.5	0.66	0.25
Ceiling	0.25	0.165	0.5
Floor	0.25	0.165	0.25

Weather and Shielding Factors (wsf)

We have shown that the weather data files are different between fan sizing and HENGH simulations, and we have also highlighted the different leakage distributions assumed. The next step was to assess how these factors impacted the infiltration estimates used in fan sizing. So, we calculated custom WSF using the same calculation methods outlined in Turner et al. and applied them to the prototype homes that we simulated using REGCAP. We then used these custom wsf to predict infiltration airflows, all of which were compared to the assumptions used in fan sizing.

With the exception of CZ16 in Blue Canyon, we found very reasonable agreement between the wsf published in ASHRAE 62.2 and those generated directly from our simulation data. These values are plotted in Figure 36, with climate indicated by symbol color, and prototype by shape (Large, 2-story homes are circles; Med, 1-story homes are triangles). Within each prototype and climate zone there is some variability by airtightness. The grey dashed lines have a slope of 1 and intercept 0, representing exact agreement for the medium and large prototypes. The colored dashed lines represent linear model of custom wsf based on simulation outputs. The outlier nature of CZ16 is clear in this plot, with values roughly 0.1 higher than those used in the standard. The rest have some scatter high or low, but are generally well-aligned with the standard.

Figure 36 Comparison of ASHRAE 62.2-2016 wsf factors and those generated directly from our simulation outputs. CZ distinguished by color, prototype by shape.



The effects of this variation on predicted effective infiltration rates are shown in Figure 37. The 1-story medium prototypes (red dashed line) overlap nearly perfectly with the ASHRAE 62.2-2016 infiltration values (Qinf), while the 2-story large prototypes (blue line) are slightly higher on average, though we expect this is driven by the CZ16 behavior. Based on these results, we conclude that with the exception of CEC CZ16, the infiltration predictions from 62.2 are more than adequate for sizing ventilation fans.

Figure 37 Predicted effective infiltration airflows from ASHRAE 62.2-2016 versus effective average airflows from the REGCAP simulations. Dashed red line shows Medium, 1-story prototype linear model, and the blue line shows the Large, 2-story model.