ERNEST ORLANDO LAWRENCE
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Development of an Outdoor Temperature-Based Control Algorithm for Residential Mechanical Ventilation Control

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2014

Environmental Energy Technologies Division

Disclaimer

Acknowledgment

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

We would like to acknowledge the efforts, feedback and support provided by our collaborators on this project, including Paul Francisco, Mike Lubliner, Don Stevens, Sarah Widder, Eric Martin, Larry Brand and Max Sherman.

Executive Summary

Smart ventilation systems use controls to ventilate more during those periods that provide either an energy or IAQ advantage (or both) and less during periods that provide a disadvantage. Using detailed building simulations, this study addresses one of the simplest and lowest cost types of smart controllers—outdoor temperature-based control. If the outdoor temperature falls below a certain cut-off, the fan is simply turned off. The main principle of smart ventilation used in this study is to shift ventilation from time periods with large indoor-outdoor temperature differences, to periods where these differences are smaller, and their energy impacts are expected to be less. Energy and IAQ performance are assessed relative to a base case of a continuously operated ventilation fan sized to comply with ASHRAE 62.2-2013 whole house ventilation requirements. In order to satisfy 62.2-2013, annual pollutant exposure must be equivalent between the temperature controlled and continuous fan cases. This requires ventilation to be greater than 62.2 requirements when the ventilation system operates. This is achieved by increasing the mechanical ventilation system airflow rates.

There were four steps to this analysis:

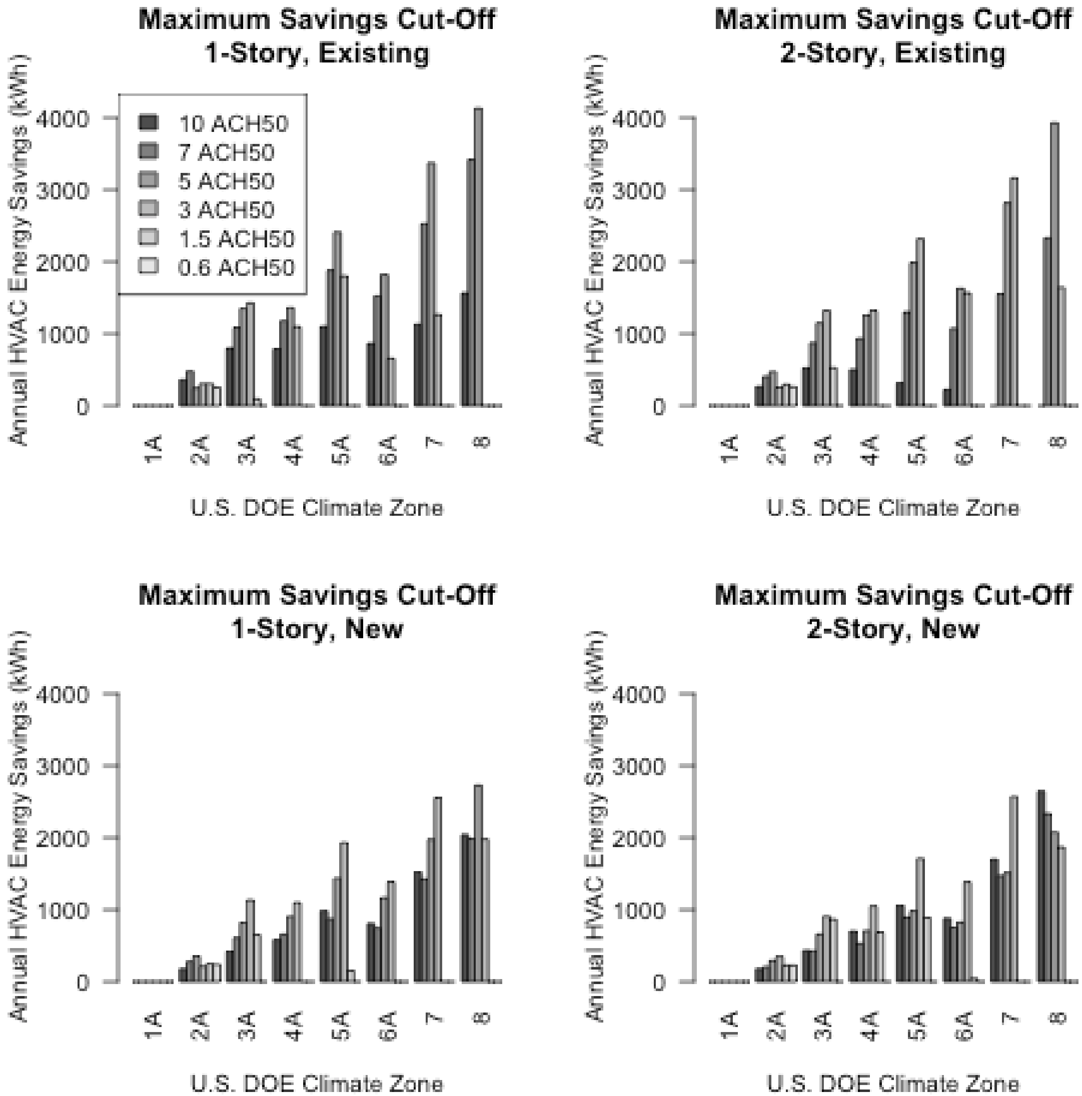
1. The outdoor temperature cut-offs were calculated—either as a fixed temperature (5°C), a fixed percentile ($Q25^{th}$)[1], or based on infiltration estimates (Inf and Inf2) using the stack part of the enhanced ventilation model (AIM-2) in the ASHRAE Handbook of Fundamentals.
2. The REGCAP simulation tool was used to estimate the energy savings and IAQ impacts of using these cut-offs to control a mechanical exhaust fan. The simulated fans were not oversized and not compliant with 62.2-2013.
3. Exhaust fans were resized to maintain equivalence with 62.2-2013 using an iterative optimization procedure that incorporated both the stack and wind parts of the AIM-2 ventilation model.
4. The REGCAP simulation tool was used to calculate energy use and relative exposures, using oversized fans that provided equivalence with 62.2-2013.

As shown in the figure below, new and existing, single- and two-story test homes from 10 to 3 ACH_{50} had substantial energy savings from the control of ventilation systems based on outdoor temperature, while maintaining equivalence with ASHRAE 62.2-2013 through fan oversizing. These savings reflect the maximum energy reduction estimate of the four temperature cut-off types (5°C, $Q25^{th}$, Inf and Inf2), for each combination of climate zone, airtightness, stories and house age. Limited savings were realized in milder climates for tighter homes of 1.5 ACH_{50}. Temperature control is not recommended in climate zone 1 or in 0.6 ACH_{50} cases. In most cases, savings were greatest in 3 and 5 ACH_{50} homes. Annual HVAC energy

[1] 25^{th} percentile of annual hourly temperatures from TMY3 data files.

savings ranged from approximately 100 kWh to 4,000 kWh (0.1 to 6% of total HVAC energy use). Absolute energy reductions generally increased with climate severity, though percentage savings were more consistent across climates. As characterized by 10 through 5 ACH_{50} cases, existing home savings were greater than those in new homes (excluding the leakiest homes with no mechanical fan requirement per 62.2). Fans were oversized by an average of 34% (ranging from approximately 5% to 150%), and equivalence with 62.2-2013 was maintained in all of these cases.

As a general guiding principle, energy savings increased as mechanical fan runtime was reduced, resulting from higher cut-off temperatures. Reductions in runtime required larger fan sizes in order to maintain equivalence with 62.2. This dynamic was not consistent in more airtight homes, where higher cut-off temperatures often necessitated much larger fans to maintain equivalence, which actually increased total HVAC energy use. The simplest strategy (a 5°C cut-off) was the most effective across a variety of climate zones, though it was not effective in all recommended cases. Our guidance for temperature control strategies is robust, though not optimal, as higher cut-offs with higher energy savings can be calculated. We recommend that tools be developed to calculate the best temperature cut-offs for varying airtightnesses and climate zones. Finally, this was a narrow investigation of smart ventilation control based on outdoor temperature, and while we make recommendations within this realm, there may be other smart ventilation strategies that are lower cost, more robust or more effective.



Maximum Savings Cut-Off
1-Story, Existing
Maximum Savings Cut-Off
2-Story, Existing
Maximum Savings Cut-Off
1-Story, New
Maximum Savings Cut-Off
2-Story, New
10 ACH50
7 ACH50
5 ACH50
3 ACH50
1.5 ACH50
0.6 ACH50
Annual HVAC Energy Savings (kWh)
0
1000
2000
3000
4000
1A
2A
3A
4A
5A
6A
7
8
U.S. DOE Climate Zone

Table of Contents

Index of Tables

Index of Figures

1 Introduction

Currently, the most common implementation of whole house mechanical ventilation is to install a small, quiet fan that operates continuously. Many such fans require less than 20 watts to operate (Home Ventilating Institute, 2014)), and the vast majority of their energy impact is due to conditioning of the ventilation air (Walker & Sherman, 2008). As building envelope performance increases with improvements to energy codes and standards, the contribution of ventilation—natural and mechanical—to overall energy use increases and presents an opportunity for energy savings. In addition, reducing the energy impacts of ventilation should help to mitigate the resistance against providing mechanical ventilation common in much of the residential building industry. Accordingly, as high performance homes become the norm in U.S. new and existing construction, demand has grown for ways to limit the energy impacts of these systems, while still providing the same IAQ and comfort benefits. *Smart ventilation* is the way in which energy savings can be achieved while not negatively impacting indoor air quality (IAQ).

Smart ventilation systems use controls to ventilate more during those periods that provide either an energy or IAQ advantage (or both) and less during periods that provide a disadvantage. They do this without compromising IAQ relative to a continuous fan sized to current ventilation standards (i.e., ASHRAE 62.2-2013) by using the equivalence principles (Max H. Sherman, Mortensen, & Walker, 2011; Max H. Sherman, Walker, & Logue, 2012). Maintaining equivalence means that pollutant exposure using ventilation control is the same or lower than when using a continuous fan (exposure calculations are described in the Methods section below). A recent interpretation to ASHRAE Standard 62.2-2013 (ANSI/ASHRAE, 2013, p. 2) added Section 4.6, which allows the use of smart ventilation technologies that ensure equivalent annual exposure, but currently no jurisdiction has specifically approved its use.

Smart whole house mechanical ventilation controls are not common in the residential buildings market. Some simple controls are fairly common in U.S. homes, including timers, motion sensors, and humidistats; all of which operate almost exclusively in bathrooms. While rare, systems that control whole house mechanical ventilation exist, such as the *FanCycler* ("FanCycler.com - Improving Air Quality," n.d.) or the *Healthy Climate Ventilation Control System* by Lennox (Lennox, 2005). But they do not control the system in such a way as to explicitly provide equivalence and compliance with 62.2-2013, namely because fans are not specifically oversized (relative to 62.2-2013) to reduce exposure during periods when the fan does operate. Other home ventilation controls are designed to save energy, such as outdoor air economizers (e..g, *NightBreeze* (Davis Energy Group, 2004)). These could be a very effective part of a smart control system, but as currently implemented, they do not ensure equivalence, and could possibly worsen IAQ, due to introduction of outdoor pollutants (filtration could mitigate this). Recent developments in residential smart ventilation controls have shown the potential to save energy while maintaining equivalence to continuously operated fans, using simple time-of-day controls (for example, in the RIVEC controller (Max H. Sherman & Walker, 2011)).

This study builds on that previous work by investigating the potential for outdoor temperature based ventilation control. The key principle is to shift ventilation from time periods with large indoor-outdoor temperature differences, to periods where these differences are smaller, and their energy impacts are expected to be less. At higher temperature differences, the energy required to condition the ventilation air is high, and the driving forces for natural infiltration are large. This means that the energy savings potential of the strategy should be strong, and the impacts of fan control on IAQ should be relatively small due to increased infiltration rates. Others have demonstrated the energy savings potential of outdoor temperature based ventilation control in residences (Lubliner, 2013; Temple & Holton, 2003), but they used simplified energy estimation tools, and they were not based on current ventilation standards (i.e., 62.2-2013) or the requirement of equivalence when using smart controls.

In this study, ASHRAE 62.2-2013 was used as the reference ventilation standard, and smart controls were used to ensure that exposure to pollutants when using temperature control did not increase relative to a continuous fan, when averaged across a whole year. Maintaining equivalence requires that ventilation airflows be higher at the lower temperature differences, which requires installation of a larger fan. The amount of oversizing depends on how much time is spent at reduced ventilation rates. This study used a simplified ventilation model and an iterative optimization process to estimate fan sizing needs to achieve equivalent ventilation. In this work, four alternative strategies based on outdoor temperatures were examined to find the best approaches. These strategies were evaluated using the REGCAP ventilation simulation tool to determine energy savings and equivalent IAQ.

2 Controller Evaluation and Development

Outdoor temperature control strategies were assessed using detailed annual simulations for potential energy savings and impacts on IAQ relative to a base case of a continuously operated fan, sized according to 62.2-2013. The equivalence calculations included the contribution of natural infiltration. Therefore the 62.2-2013 total ventilation rate was adjusted for the natural infiltration credit when determining the size of the continuously operating fan. The house location, number of stories and airtightness were all varied to capture a range of scenarios reflective of new and energy retrofitted existing homes. The control function turned the whole house mechanical ventilation fan off when outdoor temperatures dropped below specified cut-offs. Both infiltration-dependent and infiltration-independent cut-offs were assessed using simulations.

Initial detailed annual simulations were run using the LBNL REGCAP simulation model to examine the effects on IAQ if the fans are not resized. These simulations provided initial estimates of the energy and IAQ impacts of temperature control, though the resulting lower ventilations rates and associated increases in annual average exposure meant that the ventilation systems were not in compliance with 62.2-2013, and would not provide acceptable IAQ.

In order to achieve equivalent ventilation, a higher mechanical ventilation flow rate is required for when the mechanical ventilation system is operating. This larger flow rate is required to make up for reduced air exchange during periods when the temperature controller turns the fan off. A custom tool was built in Microsoft Excel in order to calculate the larger fan flow rates required to achieve IAQ equivalence with the continuous fan. This tool used the simplified enhanced ventilation model in ASHRAE Handbook of Fundamentals (HoF) Ventilation and Infiltration chapter to estimate the natural infiltration on an hour-by-hour basis for the year. Two different approaches to combining natural and mechanical ventilation were investigated: the quadrature approach in the ASHRAE HoF and the half-linear approach (Palmiter & Bond, 1991). Using these larger fan sizes REGCAP simulations were used to determine the energy use and IAQ (in terms of annual average relative exposure).

In summary, there were four steps to this analysis:

1. The outdoor temperature cut-offs were calculated—either as a fixed temperature (5°C), a fixed percentile ($Q25^{th}$) [2] or based on infiltration estimates using the stack part of the enhanced ventilation model (AIM-2) in the ASHRAE Handbook of Fundamentals Ventilation and Infiltration Chapter.
2. The REGCAP simulation tool was used to estimate the energy savings and IAQ impacts of using these cut-offs to control mechanical ventilation. The simulated fans were not oversized and therefore not compliant with 62.2-2013.
3. Ventilation fans were resized to maintain equivalence with 62.2-2013 using an iterative optimization procedure that incorporated both the stack and wind parts of the AIM-2 ventilation model.
4. The REGCAP simulation tool was used to calculate energy use and relative exposures, using oversized fans that provided equivalence with 62.2-2013.

[2] Temperature at the 25^{th} percentile of coldest hours determined from TMY data files.

2.1 Description of the Test Home

The test home is a 3-bedroom home with finished floor area of 195 m^2 (2,100 ft^2) and conditioned volume of 488 m^3 (17,234 ft^3). The test home was simulated in the U.S. DOE climate zones and representative cities listed in Table 3. Table 1 summarizes the building envelope R-values. A vented attic containing the house HVAC system was simulated, with medium color asphalt shingles for roof cladding. The total glazing area was 39 m^2, distributed proportionally according to the wall areas. Table 2 summarizes the Effective Leakage Area (ELA) and Normalized Leakage (nL) that ranged from Passive House levels of 0.6 ACH_{50} to 10 ACH_{50} typical of older, retrofitted homes (and close to the geometric mean of all U.S. homes in the LBNL Air Leakage Database (Chan, Joh, & Sherman, 2013). The ELA was combined with an assumed pressure exponent of 0.67 to determine the flow coefficient (c) for input to the infiltration models. The nL was used in the 62.2-2013 infiltration credit calculations. All heating systems are 80% AFUE natural gas furnaces, and all homes had vapor compression cooling systems with Energy Efficiency Ratios (EER) of 11. ACCA Manual J (2011) was used to determine heating and cooling system capacities. Heating air handler flow rate was assumed to be 16.8 cfm/kBtu-hr, and the cooling air handler flow rate was 189 L/s (400 cfm) per ton of rated capacity. Ducts were all located in the vented attic with R-8.7 hr-ft^2-°F/btu duct insulation. Supply and return duct leakages were both 3%, for a total leakage of 6%. Ancillary exhaust fans were also included in the simulations, including a vented clothes dryer (71 L/s, 150 cfm), kitchen exhaust (47 L/s, 100 cfm) and two bathroom exhaust fans (24 L/s, 50 cfm). Turner & Walker (2012) documented a restrained semi-random approach to scheduling exhaust fans in REGCAP simulations (Turner & Walker, 2012), which we used in this work.

The heating thermostat setting was 20.0°C (68°F) from 12 am to 8:59 am and 21.1°C (70°F) from 9am to 11:59pm. The cooling thermostat setting was 23.3°C (74°F) from 6:00 pm to 8:59 am and 26.7°C (80°F) from 9:00 am to 5:59 pm. Internal heat gains did not vary with time of day or time of year. Sensible heat gains were assumed to be 628.9 watts, and latent heat gains were 277 watts. The internal moisture generation rate was assumed to be 9.8 kg/day (21.6 lbs/day).

		DOE Climate Zone														
		1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7	8
Term	Unit	R-Value														
Walls	ft^2 °F hr/Btu	13	13	13	13	13	13	13	13	20	20	20	20	20	21	21
Windows	ft^2 °F hr/Btu	1.5	1.5	1.5	2.0	2.0	2.0	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9	2.9
Doors	ft^2 °F hr/Btu	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
Floor	ft^2 °F hr/Btu	13	13	13	19	19	19	19	19	19	30	30	30	30	38	38
Ceiling	ft^2 °F hr/Btu	30	30	30	30	30	30	38	38	38	38	38	49	49	49	49

Table 1 Building Assembly R-Value Model Inputs

ACH_{50}	1-Story		2-Story	
	ELA (m^2)	nL	ELA (m^2)	nL
10	0.097	0.507729	0.097	0.669952
7	0.068	0.35541	0.068	0.468967
5	0.048	0.253864	0.048	0.334976
3	0.029	0.152319	0.029	0.200986
1.5	0.015	0.076159	0.015	0.100493
0.6	0.006	0.030464	0.006	0.040197

Table 2 Building leakage assumptions

U.S. DOE Climate Zone	City	TMY3 ID
1A	Miami	722020
2A	Houston	722430
2B	Phoenix	722780
3A	Memphis	723340
3B	El Paso	722700
3C	San Francisco	724940
4A	Baltimore	724060
4B	Albuquerque	723650
4C	Salem	726940
5A	Chicago	725300
5B	Boise	726810
6A	Burlington	726170
6B	Helena	727720
7	Duluth	727450
8	Fairbanks	702610

Table 3 List of U.S. DOE climate zones, representative cities and associated TMY3 IDs.

Mechanical Ventilation System Sizing

The whole house ventilation fan was sized to meet ASHRAE 62.2-2013 requirements. The analysis examined both new and existing homes approaches in ASHRAE 62.2. An exhaust fan was used as this is the simplest and most common type found in homes. Both supply and exhaust fans are expected to give similar results, due to imbalanced fan interactions with natural infiltration. As the intent of this study was to develop a low-first-cost controller, heat and energy recovery ventilators (HRVs and ERVs) were not investigated. In addition, HRV/ERV systems are expected to show smaller energy impacts, because their energy use is significantly reduced compared to some supply or exhaust fans, and the energy savings for more advanced controllers are expected to be much smaller.

The total ventilation rate (Q_{tot}) was calculated using Equation 1, and the annual average infiltration (Q_{inf}) was estimated using Equation 2. The mechanical ventilation fan (Q_{fan}) was then sized according to Equation 3, as the total ventilation rate minus the estimated infiltration rate. Equation 4.6 in ASHRAE 62.2-2013 limits Q_{inf} to no greater than 2/3 Q_{tot} in new homes, so a fan with airflow of 14.4 L/s was specified ($Q_{tot}/3$) in these cases. Essentially, this ensures that all new homes have a mechanical ventilation fan, no matter their air leakage levels, in order to protect against periods of low driving forces. Fan power was calculated assuming 0.4361 watts per L/s of fan flow, which was derived by averaging the Home Ventilation Institute (HVI) rated watts per L/s of a number of Energy Star certified ventilation fans. Each combination of climate zone, airtightness and number of stories resulted in a different fan flow rate and energy use.

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

Q_{tot} = total required ventilation rate, L/s
A_{floor} = conditioned floor area, m^2
N_{br} = number of bedrooms

Equation 1 ASHRAE 62.2-2013 Total Required Ventilation Rate, Equation 4.1b

$$Q_{inf} = \frac{NL \times wsf \times A_{floor}}{1.44}$$

Q_{inf} = effective annual average infiltration rate, L/s
NL = normalized leakage
wsf = weather and shielding factor (normative appendix B)
A_{floor} = floor area, m^2

Equation 2 ASHRAE 62.2-2013 Effective annual average infiltration rate, Equation 4.5b.

$$Q_{fan} = Q_{tot} - Q_{\mathrm{inf}}$$

Q_{fan} = required mechanical ventilation rate, L/s
Q_{tot} = total required ventilation rate, L/s
Q_{inf} = effective annual average infiltration rate, L/s

Equation 3 ASHRAE 62.2-2013 Required Mechanical Ventilation Rate, Equation 4.6

Existing Home Adjustments

This temperature control strategy may also be appropriate in existing residences that have been airtightened and received a mechanical ventilation fan, as is required in the U.S. DOE Weatherization program (U. S. DOE, 2011, p. 2). Installation of 62.2-compliant mechanical ventilation systems in weatherized Wisconsin homes (not 62.2-2013), has been shown to provide some IAQ benefits (i.e., modest reductions in CO_2 and humidity) in a subset of homes, namely those with airtight envelopes and higher occupant densities (Pigg et al., 2011).

A common scenario in such homes is that bathroom and kitchen exhaust fans are either inadequate or non-existent, and the whole house mechanical fan is over-sized to compensate for this deficit, per the requirements contained in the *Normative Appendix A—Existing Buildings* in 62.2-2013. Essentially, the appendix states that if local exhaust flows in bathrooms and kitchens do not satisfy the local exhaust requirements of the standard, then the whole house ventilation rate is to be increased by the total airflow deficit ($Q_{deficit}$) divided by four (see Equation 4). Flow deficits in actual existing homes will vary, depending on existing conditions. Our existing home cases simply illustrate one example assuming a total flow deficit of 65 L/s (50 L/s for no kitchen exhaust and 15 L/s for a bathroom with no fan and an operable window). This increased $Q_{tot,existing}$ from 43.3 L/s in the new home test cases to 59.6 L/s in the existing home test cases. This also led to an increase in the air exchange rate, A_{eq}, used in the equivalence calculations. This means that an existing home with the same envelope leakage as a new home will have different results for equivalent exposure calculations, fan sizing and energy use.

$$Q_{tot,existing} = Q_{tot} + \left[\frac{Q_{deficit}}{4}\right]$$

$Q_{tot,existing}$ = Total ventilation rate in an existing home, L/s
Q_{tot} = Total ventilation rate, L/s
$Q_{deficit}$ = Flow deficit based upon bathroom and kitchen fans in an existing home, L/s

Equation 4 Total ventilation rate calculation, existing home case.

2.2 Temperature Control Strategies

At the outset, we anticipated that higher temperature cut-offs would result in higher energy savings, subject to the constraint that systems must maintain equivalence with a continuous 62.2-2013 ventilation system. The point at which equivalence could not be maintained was expected to vary with climate zone and airtightness. At some point, the fan would be turned off for too many hours, infiltration would be too low during these periods (either due to increased airtightness or to lower driving forces, or both), and an oversized fan of reasonable proportions would not be able to maintain equivalence. It was not clear how to find this balance between higher cut-offs (and more time with the fan turned off) and fan oversizing (and equivalence), so a variety of temperature cut-off types were tested.

Four temperature control strategies were developed using *infiltration-dependent* and *infiltration-independent* cut-off temperatures, as described in Table 4. The infiltration-independent cut-offs were either constant (5°C), or varying only by climate zone ($Q25^{th}$) and not house characteristics. This simplicity would be beneficial when implementing temperature control strategies in actual homes, but only if the energy performance was similar or better than infiltration-dependent cut-offs. These are more complex to calculate and depended on house leakage and house geometry.

Name	Type	Variability	Description
Inf	Infiltration-dependent	Varies with house airtightness, number of stories and floor area. Does not vary by climate zone.	Temperature at which natural infiltration stack airflow is 100% of Q_{tot}. Turn fan off below temperature.
Inf2	Infiltration-dependent	Same as Inf.	Adding a second temperature cutoff to Inf at 50% of Q_{tot}, at which point the fan is operated at half flow.
5°C	Infiltration-independent	Does not vary with house or climate.	Fixed 5˚C for all cases. Turn fan off below temperature.
Q25[th]	Infiltration-independent	Varies by climate zone, but not house characteristics.	Temperature at the 25[th] percentile of coldest hours determined from TMY data files. Turn fan off below temperature.

Table 4 Summary description of the four temperature control strategies.

Infiltration-Dependent Cut-Offs

For the purposes of generating infiltration-dependent cut-off temperatures (i.e., Inf and Inf2), the new and existing test case homes were assessed in one- and two-story configurations, all with identical total floor areas, volumes, bedrooms and leakage areas. Airtightness was varied across a wide range—10, 7, 5, 3, 1.5 and 0.6 ACH_{50}. Infiltration was estimated using the stack airflow equation provided for the Enhanced Model for residential ventilation and infiltration (also known as AIM-2) model in the ASHRAE Handbook of Fundamentals (Equation 49) (ASHRAE Handbook of Fundamentals, "Ventilation and Infiltration," 2013) as shown in Equation 5[3]. This equation was rearranged and solved for the outdoor temperature, as shown in Equation 6. The temperature cutoff was calculated by substituting Q_{tot} from ASHRAE 6.2-2013 for Q_s into Equation 6. It was also assumed that the pressure exponent, n, was equal to 0.67—the same as used in the REGCAP simulations. Enhanced model coefficients were retrieved from the ASHRAE Handbook of Fundamentals, Table 8 (all assumed the presence of a flue).

The cutoff temperature is then the outdoor temperature at which stack infiltration (Q_s) equals the total ventilation requirement for 62.2-2013, and therefore a fan is no longer required. This calculation was repeated to find the cutoff temperature using one half Q_{tot} to find the 50% cutoff temperature. Note that this approach uses the same assumption as 62.2-2013 that natural infiltration and unbalanced fan flows may be added linearly. This is a significant simplification and tends to over predict

[3] Only the stack portion of ventilation was used, because this study only investigates the use of temperature controls. Reliable and robust onsite wind speed measurements are currently not available (and are unlikely to be so in the future). Therefore the wind driven potion of natural infiltration cannot be included in the controller.

the net-effect (Kiel & Wilson, 1987; Li, 1990; Palmiter & Bond, 1991; Max H. Sherman, 1992; Wilson & Walker, 1990). Cut-off temperatures varied as a strong function of airtightness and house geometry. Temperatures calculated using Equation 6 are presented in Table 5 (new home test case) and Table 6 (existing home test case) for 100% and 50% of Q_{tot} requirements for one and two story test cases.

TMY3 weather files were analyzed to find the fraction of the year in each climate below the cutoff temperatures to give an idea of how often this control strategy would turn off (or turn down for the 50% case) the whole house fan. The percentage of annual hours below these 100% and 50% cut-offs are provided (for new homes) in Table 7 and Table 8, for 1- and 2-story test cases, respectively. Periods of fan control varied from 0% of annual hours to over 60%. In the more airtight test cases, the infiltration-dependent cut-offs were so low (i.e., less than -200°C) that outside temperatures never reach these cut-offs, even in the most severe climate tested. This eliminated the benefits of infiltration-based temperature control in the 1.5 and 0.6 ACH_{50} test cases that are omitted from these tables, and severely restricted the benefits in 3 ACH_{50} test cases.

$$Q_s = c * C_s * \Delta T^n$$

Q_s = stack airflow, m^3/s
c = house flow coefficient, $m^3/(s*Pa^n)$
C_s = stack coefficient, $(Pa/K)^n$
ΔT = temperature differential, K
n = house pressure exponent

Equation 5 Stack airflow equation.

$$T_{cutoff} = T_{setpoint} - \left[\frac{Q_s}{c * C_s}\right]^{\left(\frac{1}{n}\right)}$$

T_{cutoff} = outside temperature cut-off, K
$T_{setpoint}$ = house thermostat set-point, K
Q_s = stack airflow, m^3/s
c = house flow coefficient, $m^3/(s*Pa^n)$
C_s = stack coefficient, $(Pa/K)^n$
n = house pressure exponent

Equation 6 Infiltration based cut-off temperature calculation.

Airtightness (ACH_{50})	100% Q_{tot}		50% Q_{tot}	
	One Story (°C)	Two Story (°C)	One Story (°C)	Two Story (°C)
10	4.2	9.2	14.4	16.2
7	-6.9	1.6	10.5	13.5
5	-24.4	-10.4	4.2	9.2
3	-75.1	-45.1	-13.8	-3.1
1.5	-247.7	-163.1	-75.1	-45.1
0.6	-1030.8	-698.7	-353.4	-235.4

Table 5 Stack-only ventilation cut-off temperatures, new home cases. Valid ONLY for 195 m² test case home.

Airtightness (ACH_{50})	100% Q_{tot}		50% Q_{tot}	
	One Story (°C)	Two Story (°C)	One Story (°C)	Two Story (°C)
10	-5.4	2.6	11	13.8
7	-23.3	-9.6	4.6	9.5
5	-51.5	-28.9	-5.4	2.6
3	-133.3	-84.8	-34.5	-17.3
1.5	-411.4	-275	-133.3	-84.8
0.6	-1673.5	-1138.2	-581.8	-391.6

Table 6 Stack-only ventilation cut-off temperatures, existing home cases. Valid ONLY for 195 m² test case home.

U.S. DOE Climate Zone	10 ACH50		7 ACH50		5 ACH50		3 ACH50	
	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}
1A	0%	4%	0%	1%	0%	0%	0%	0%
2A	4%	23%	0%	14%	0%	4%	0%	0%
2B	1%	20%	0%	9%	0%	1%	0%	0%
3A	12%	37%	1%	27%	0%	12%	0%	0%
3B	7%	36%	0%	24%	0%	7%	0%	0%
3C	0%	59%	0%	17%	0%	0%	0%	0%
4A	22%	52%	2%	39%	0%	22%	0%	0%
4B	21%	51%	0%	39%	0%	21%	0%	0%
4C	14%	67%	0%	46%	0%	14%	0%	0%
5A	35%	59%	8%	49%	0%	35%	0%	2%
5B	27%	63%	1%	49%	0%	27%	0%	0%
6A	38%	66%	10%	55%	0%	38%	0%	3%
6B	41%	72%	10%	60%	0%	41%	0%	3%
7	49%	75%	21%	63%	1%	49%	0%	9%
8	58%	82%	39%	70%	7%	58%	0%	27%

Table 7 Percentage of annual hours where estimated stack infiltration provides 50% and 100% of Q_{tot}.. 1-story test cases. Valid ONLY for 195 m² test case home.

U.S. DOE Climate Zone	10 ACH50		7 ACH50		5 ACH50		3 ACH50	
	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}	100% Q_{tot}	50% Q_{tot}
1A	0%	7%	0%	3%	0%	0%	0%	0%
2A	12%	29%	2%	22%	0%	12%	0%	0%
2B	6%	27%	0%	18%	0%	6%	0%	0%
3A	24%	43%	8%	36%	0%	24%	0%	2%
3B	20%	43%	3%	35%	0%	20%	0%	0%
3C	10%	78%	0%	51%	0%	10%	0%	0%
4A	36%	58%	15%	50%	1%	36%	0%	6%
4B	36%	58%	13%	50%	0%	36%	0%	3%
4C	39%	76%	6%	64%	0%	39%	0%	2%
5A	46%	66%	26%	58%	4%	46%	0%	14%
5B	45%	70%	18%	61%	1%	45%	0%	5%
6A	52%	73%	31%	65%	6%	52%	0%	18%
6B	57%	79%	32%	70%	5%	57%	0%	18%
7	60%	82%	42%	73%	15%	60%	0%	29%
8	68%	88%	53%	80%	33%	68%	0%	45%

Table 8 Percentage of annual hours where estimated stack infiltration provides 50% and 100% of Q_{tot}.. 2-story test cases. Valid ONLY for 195 m² test case home.

Infiltration-Independent Cut-Offs

In an attempt to extend energy savings for outside temperature-based control to tighter homes, infiltration-independent cutoff temperatures were also tested. These included a simple 5°C cut-off, as well as a cut-off temperature calculated as the 25th percentile of annual hourly temperatures for that climate zone using TMY3 data (see Table 9). These cut-offs did not vary with airtightness or age of home. For reference, the percentages of annual hours with temperatures below cut-offs in addition to 5°C (e.g., -10°C, -5°C, etc.) are provided in Table 10.

U.S. DOE Climate Zone	25th Percentile Temperature (°C)
1A	22.2
2A	15
2B	15.6
3A	9.4
3B	10.6
3C	11.1
4A	5
4B	5.6
4C	6.7
5A	1.1
5B	3.3
6A	-0.6
6B	-0.6
7	-5
8	-14.4

Table 9 25th percentile cut-off temperatures.

DOE CZ	-10°C	-5°C	0°C	***5°C***	10°C
1A	0%	0%	0%	***0%***	0%
2A	0%	0%	0%	***1%***	8%
2B	0%	0%	0%	***1%***	12%
3A	0%	0%	1%	***5%***	13%
3B	0%	0%	2%	***9%***	22%
3C	0%	1%	4%	***16%***	42%
4A	0%	1%	5%	***13%***	26%
4B	0%	1%	8%	***23%***	38%
4C	1%	3%	11%	***24%***	37%
5A	1%	3%	13%	***29%***	47%
5B	4%	10%	20%	***36%***	47%
6A	5%	13%	26%	***43%***	59%
6B	6%	13%	26%	***40%***	54%
7	15%	24%	37%	***50%***	62%
8	33%	42%	50%	***58%***	69%

Table 10 Percentage of annual hours below potential infiltration-independent cut-off temperatures

Selecting the Best Temperature Cut-Off Strategy

As discussed at the beginning of this section, we anticipated that those control strategies that turned the fan off for the most amount of time would save the most energy, provided that they could maintain equivalence. This might mean that the best strategy is simply the one with the highest cut-off temperature. For example, we have plotted the cut-off temperatures for the 10 and 7 ACH_{50}, 1-story new Inf cases in Figure 1 and Figure 2, where they are compared with the constant 5°C and Q25th cut-offs.

The infiltration dependent cut-off temperatures increase with floor area, and the effects of incremental changes in floor area are greatest in small homes. In our detailed simulations, we only tested a home with fixed floor area (195 m^2), but our results, namely energy savings estimates, would be different with different sized homes. This would be due to both differences in total energy use (which scales roughly with home size), as well as differences in how the ventilation control would behave. For the Inf or Inf2 cases only, smaller homes would have fewer hours of controller operation (and likely lower energy savings) due to lower cut-off temperatures, and larger homes would have turned the fan off more than in our simulations, because of higher cut-off temperatures (likely saving more energy). Our recommended strategies (based on the highest energy savings) may also shift depending on home size, but this would occur in very few cases, such as in 10 ACH_{50} 1-story test cases larger than 200 m^2 in climate zone 4, where the Inf cut-off exceeds the otherwise highest cut-off temperature (5°C).

To identify which cut-off type will perform the best for any given case and home size, it may be that one only needs to find the highest temperature among the three. For example, a 200 m^2, 1-story, 10 ACH_{50} home in CZ 3A should have the highest energy savings using the Q25th strategy, as the cutoff temperature (9.4°C) is higher than the 5°C cut-off and the infiltration cut-off (4.4°C). We expect that this rule will break down once some level of airtightness is reached. For example, in 0.6 ACH_{50} homes, the Inf cut-offs are never reached, and in mild climates the higher cut-off would generally be Q25th, but this may result in the fan being turned off for too long, and the lack of infiltration in a super airtight home may mean that equivalence cannot be achieved. In these cases, the highest cut-off may not be best; in fact, temperature controlled ventilation may not be appropriate at all in very airtight homes. We have simulated each of the four cut-off types described above in each test home case, in order to test this assumption—that the highest cut-off will reliably produce the highest energy savings.

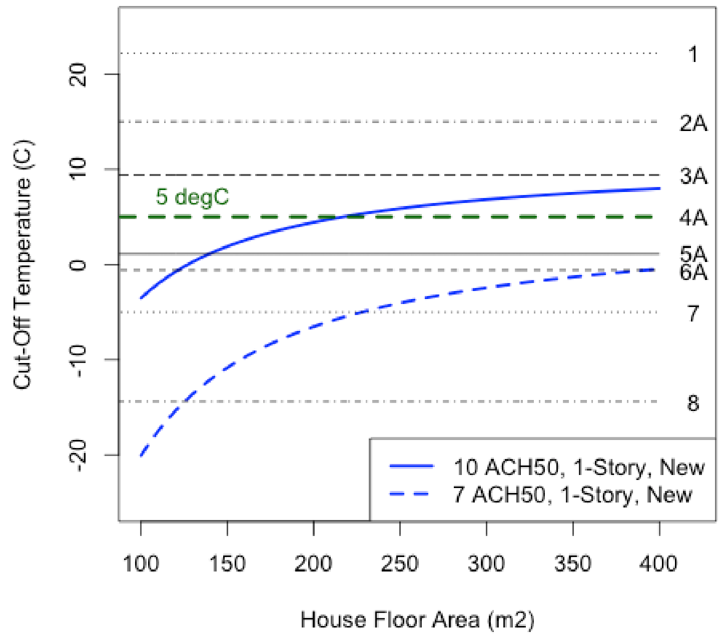


Figure 1 Comparing cut-off temperature strategies across varying home floor areas. 1-story, new example case. Infiltration dependent cut-off temperatures (in blue) vary with house floor area, and other cut-offs (5°C (green) and Q25th (black) for climate zones 1 through 8) do not vary with floor area. We expect that the highest cut-off temperature will lead to the highest energy savings, given that equivalence can be maintained through fan oversizing.

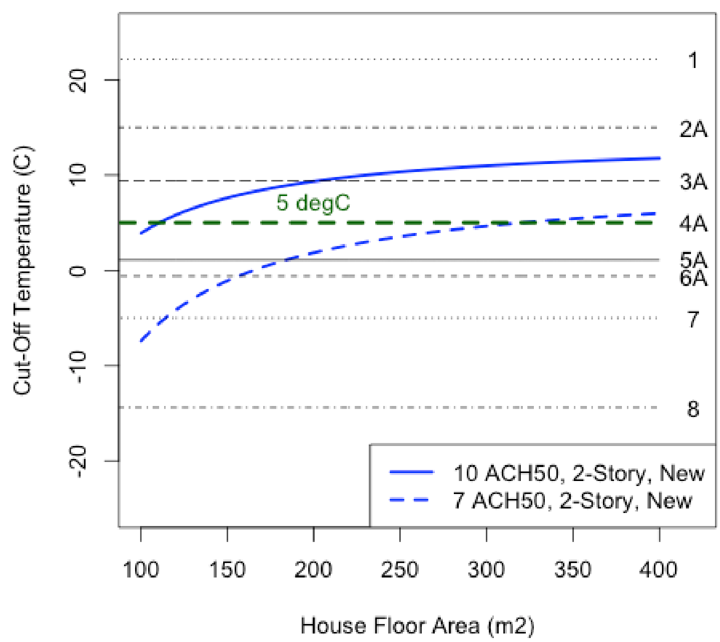


Figure 2 Comparing cut-off temperature strategies across varying home floor areas. 2-story, new example case.

2.3 Building Simulation with REGCAP

The REGCAP simulation tool[4] was used to calculate the impacts of temperature based ventilation control on annual estimates of energy use, air exchange rates, and relative dose and exposure amongst ventilation temperature control scenarios. The following parameters were varied in the simulations: (1) the U.S. DOE Climate Zones, (2) the airtightness was varied between 10, 7, 5, 3, 1.5, and 0.6 ACH_{50}, (3) number of stories, (4) new and existing homes, and (5) the cut-off temperatures. REGCAP combines models for mass-balance ventilation (including envelope, duct and mechanical flows), heat transfer, HVAC equipment and moisture. REGCAP was implemented using a one-minute time step to capture sub-hourly fan operation and the dynamics of cycling HVAC system performance. TMY3 weather data were linearly interpolated from one hour to one-minute time steps. The decision to turn the whole house fan on or off was made for each minute.

A total of 1,800 annual simulations were run with the initial, 62.2-2013 sized fans (i.e., 15 climate zones, 6 levels of airtightness, 1 and 2 stories, new and existing, and 5 fan control types), and an additional 768 annual simulations were run with fans resized to achieve equivalent IAQ (i.e., 8 climate zones, 6 levels of airtightness, 1 and 2 stories, new and existing, and 4 fan control types), for a total of 2,568 simulations. The reduced number of climate zones in the second round of simulations was due to limitations on time and resources.

2.4 Relative Exposure—Equivalence and IAQ

The metric of *annual relative exposure* was used to quantify IAQ. *Exposure* is the instantaneous concentration in the occupied space. Exposure is calculated relative to a base case that assumes a constant pollutant emission rate and air exchange rate at the ASHRAE 62.2-2013 Total Ventilation Rate requirement (Q_{tot}, see Equation 1). In practice, if the annual average relative exposure is exactly equal to 1, then we can say that the occupants have received the equivalent exposure to indoor contaminants to what they would have received in a house with a continuously operating mechanical ventilation system that is operating at the ASHRAE 62.2-2013 minimum airflow rate (Q_{tot}). An annual average relative exposure below unity indicates over-ventilation for the year, and an annual average relative exposure above unity indicates under-ventilation for the year. Equation 7 was used to calculate relative exposure in this research, and annual average exposure was calculated by averaging r_i for each time-step.

[4] The REGCAP model is described in detail in Appendix 1 of (Walker & Sherman, 2006).

$$R_i = \left[\left(\frac{A_{eq}}{AER_i}\right)(1 - e^{-AER_i \times \tau})\right] + R_{i-1}e^{-AER_i \times \tau}$$

R_i = relative exposure at time-step $_i$
R_{i-1} = relative exposure at time-step $_{i-1}$
A_{eq} = Air exchange rate against which equivalence is assessed (Q_{tot}), hr^{-1}
AER_i = Actual air exchange rate at time-step i, hr^{-1}
τ = Time-step, hr

Equation 7 Relative exposure.

Because REGCAP simulations are more sophisticated than the calculations used in 62.2-2013 and the simple model used for fan sizing, the resulting equivalent exposure for each simulation was not always equal to unity. Therefore, the equivalence requirement for the four temperature control strategies was compared to the equivalent exposure for the matching continuously operating fan case without the ventilation control. The equivalence calculations were renormalized by dividing by the equivalent exposure for the corresponding continuously operating fan case.

Increasing Fan Size to Achieve Equivalence

The first set of simulations performed using the REGCAP model used the exact fan sizes specified for a continuously operating ventilation system, sized according to 62.2-2013. With temperature controlled fan shut-off, this fan sizing led to small increases in relative exposure, due to lower levels of air exchange during times when the fan was turned off. No pre-existing method has been proposed to re-size a fan, in the context of a ventilation controller, in order to provide equivalence consistent with Section 4.6 of 62.2-2013, which reads:

"A whole-building ventilation system shall be designed and operated in such a way as to provide the same or lower annual exposure as would be provided by complying with Section 4.1"

Previous smart ventilation controllers (i.e., RIVEC) have simply over-sized fans in all cases by 25% and were stated to comply with Section 4.5.2 of 62.2-2013, because the fan was never turned off for more than 4-hours during any given day (Turner & Walker, 2012). The temperature-controlled strategy being assessed in this research did not have any restrictions on the total number of contiguous hours that the fan could be turned off. For example, a leaky home (e.g., 10 ACH_{50}) in a cold climate (e.g., U.S. DOE Climate Zone 8) might have the fan turned off for lengthy, uninterrupted periods of time. As a result, no fan sizing simplifications were possible.

The solution was to build a tool using Microsoft Excel, along with the add-in optimization tool Solver from Frontline Systems, in order to iteratively re-size the ventilation fan so as to maintain equivalence. The following process was used:

1. Ventilation fan sizes for continuous operation were calculated according to 62.2-2013 equations 4.1b and 4.6 (Equation 1 and Equation 3).
2. Using TMY3 hourly weather data for each of 15 representative U.S. DOE climate zones, outdoor temperature cut-off values were determined for infiltration-dependent cases with one and two cut-off temperatures (using Equation 6), as well as for infiltration-independent temperatures (i.e., 5°C and $Q25^{th}$).
3. Combined wind and stack infiltration were estimated for each hour of the year using the Enhanced Model for single-zone infiltration estimation (ASHRAE Handbook of Fundamentals, "Ventilation and Infiltration," 2013). Wind and stack flows were combined using quadrature.
4. Fan airflows (continuous and controlled) were added to the natural infiltration flows using the half-linear method from Palmiter and Bond, 1991[5].
5. These combined flows were converted to hourly air exchange rates, and relative exposures were calculated using the hourly AER and an Aeq equivalent to the value of the Total Ventilation Rate (Q_{tot}).
6. These values were averaged to generate annual average AERs and relative exposures. At this point, the temperature-controlled cases always had annual relative exposures greater than the continuous reference cases.
7. The Solver tool was then engaged to change the fan size for the temperature controlled ventilation, such that the annual relative exposure in the temperature-controlled cases was equal to or less than the continuous case. A constraint was placed on the Solver tool, limiting the fan size to less than 0.4 m^3/s (848 cfm). From a practical perspective of limited space for ducting and fans, requirements for air tempering, and availability of ventilation equipment, home ventilation systems will not be installed with air flow capacities greater than about 300-400 cfm (150-200 L/s). However, we allowed larger sizes to be evaluated in order to better observe trends in the analysis.
8. Annual average AER and relative exposure were noted for each level of airtightness, climate zone, number of stories and house age (i.e., new or existing).

[5] The half-linear model of superposition was used instead of the more commonly accepted quadrature method. For a subset of test cases, changes in annual average AER and HVAC energy use resulting from temperature based control were predicted by the quadrature and half-linear methods, and these were compared with changes predicted by the advanced REGCAP simulations. The half-linear method better reflected the AER results of the REGCAP model. Energy results were mixed, with half-linear consistently over-predicting savings and quadrature under-predicting, though the range of errors and the median error were smaller with the half-linear method. So, the half-linear method was chosen for fan resizing calculations. Future work should examine the effectiveness of different superposition techniques over a wide range of home and weather conditions to determine optimum superposition strategies. The optimum strategy may depend on the desired application, e.g., in this study the optimum strategy is the one that works best for stack dominated conditions as we are basing the control on temperature.

9. These larger fan flows were then used as inputs into the detailed REGCAP simulation, in order assess energy savings and equivalence.

3 Results

3.1 Baseline Variability in Relative Exposure

To estimate changes in energy use and IAQ, we need a baseline reference for comparison. The baseline REGCAP simulations used no ventilation control and had continuously operating fans sized according to 62.2-2013.

Exposure is intended to equal 1 when compliant with 62.2-2013, but this was not the case with the baseline REGCAP simulations. The baseline relative exposure values calculated by the REGCAP model are shown in Figure 3 for 1-story new home test cases. On average, the values for all new homes are slightly less than one (median of 0.95), suggesting some level of over-ventilation relative to the ASHRAE 62.2-2013 total ventilation rate. The variability below and above 1 reflects several interacting effects that are not easily disaggregated:

1. Intermittent air exchange provided by local exhaust fans and duct leakage.
2. Infiltration impacts resulting from variable airtightness and weather across climate zones.
3. The sub-additive nature of natural and mechanical ventilation that is not included in the 62.2 fan sizing calculations. The magnitude of this effect depends on climate and envelope leakage, and the effect is largest when natural and mechanical flows are similar in size.
4. Fan sizing effects contained in 62.2-2013 that limit the Q_{inf} value to no less than 1/3 of the Q_{tot} value.
5. Weather factors provided in 62.2-2013 use TMY3 data files and house geometries that do not exactly match those of our test cases.

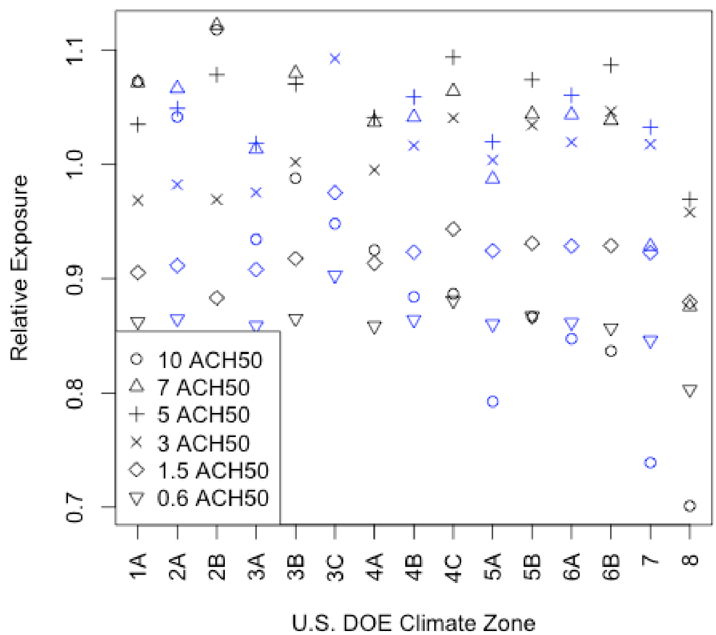


Figure 3 Annual relative exposure in base test cases.

3.2 Initial Results for Non-Compliant Ventilation System Controls

In order to the energy and IAQ impacts of simply turning off the ventilation fan in response to the outdoor temperature, a first round of simulations were performed in which the 62.2-2013 compliant fans were turned off by the temperature controllers without increasing the fan size to ventilate more at other times. It was expected that this would result in relative exposures that were too high—and these high relative exposures would indicate the need for a smarter approach to ventilation control—namely the application of relative exposure calculations and resized fans. The results in this section are therefore for comparison purposes only, as they do not comply with requirements to maintain relative exposure as required by smart ventilation principles and in the interpretation of 62.2-2013.

Increases in relative exposure are summarized in Table 11. They varied from 0% to less than 5% in all infiltration dependent cut-off scenarios (Inf and Inf2), but they strongly scaled with airtightness in the infiltration independent cut-offs (Q25th and 5°C), reaching as high as 40% increases in exposure.

ACH$_{50}$	1-Story Test Cases				2-Story Test Cases			
	Inf	Inf2	Q25th	5°C	Inf	Inf2	Q25th	5°C
10	1%	4%	3%	2%	2%	3%	1%	1%
7	0%	3%	5%	3%	1%	3%	3%	1%
5	0%	2%	9%	6%	0%	3%	5%	3%
3	None	0%	17%	12%	None	1%	11%	8%
1.5	None	None	29%	24%	None	None	23%	17%
0.6	None	None	41%	35%	None	None	37%	32%

Table 11 Mean increases in relative exposure resulting from ventilation control based on outdoor temperature. NOT compliant with 62.2-2013.

Total energy reductions were highly variable depending on the control strategy, climate zone and airtightness. For example, annual HVAC energy savings for the two-story home using two infiltration cut-offs are shown in Figure 4. Within each climate zone, energy reductions were reduced as airtightness increased, and energy reductions increased with increasing climate severity (from CZ 1 to 8). More details for total annual energy savings summarized for all four temperature control strategies in Appendix 2.

When using infiltration based cut-off temperatures, the ventilation control strategy becomes more effective as homes become leakier and climates more severe. Energy reductions were also generally greater in 2-story test cases using infiltration-based cut-offs. This is because more hours of the year have outside temperatures below the cut-offs (see Table 7 and Table 8). While fan sizes were smallest in the leakiest homes (due to larger infiltration credits taken using 62.2-2013 Equation 4.5b), they were turned off for substantial periods of time, which led to the largest savings.

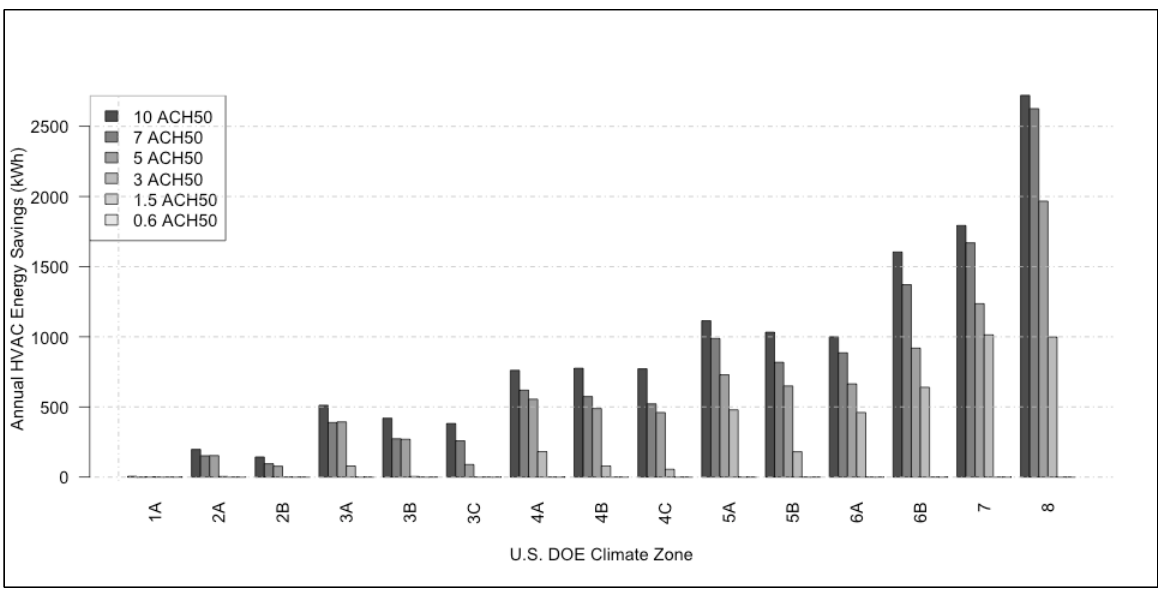


Figure 4 Two-story home using two temperature cut-offs, designed to provide 100% and 50% of the 62.2-2013 Total Ventilation Rate by natural infiltration. Fan sized to 62.2-2013 Equation 4.1b (Equation 3 above), NOT compliant with 62.2-2013.

Control strategies using infiltration independent temperature cut-offs (i.e., Q25th or 5°C) provide more energy savings as homes become more airtight and climates more severe, as shown in Figure 5. Unlike the infiltration based cut-offs, 1-story test cases had higher average energy reductions. This may be because 1-story cases have larger fan airflows than the 2-story cases, and the fans are turned off the same amount of time, no matter the height of the home. Changes in annual air exchange were larger in more airtight homes, and accordingly, exposure increased as well. This suggests that IAQ is compromised in these cases. In the most extreme cases, the infiltration independent temperature strategies appear to provide huge energy savings (e.g., 18,292 kWh in the 2-story, 5°C, 0.6 ACH_{50} case in climate zone 8), but IAQ is unacceptably worsened. In the compliant, continuous fan case for this example home, annual average AER was 0.40 and was reduced to 0.25 by the 5°C control. Similarly, annual average relative exposure went from 0.82 to 1.48, nearly a doubling of exposure for the home's occupants.

The increasing savings of non-infiltration based cut-offs in more airtight homes is only expected when fan sizes are not adjusted. In the more airtight homes, turning off the fan has a larger impact on the air exchange, energy use and relative dose (due to larger fan airflows and lower infiltration values). This means that for any fixed amount of time that the fan does not operate, a larger fan will be needed in an airtight home in order to compensate and achieve equivalence. This will likely offset some or all of the energy savings suggested by these preliminary results.

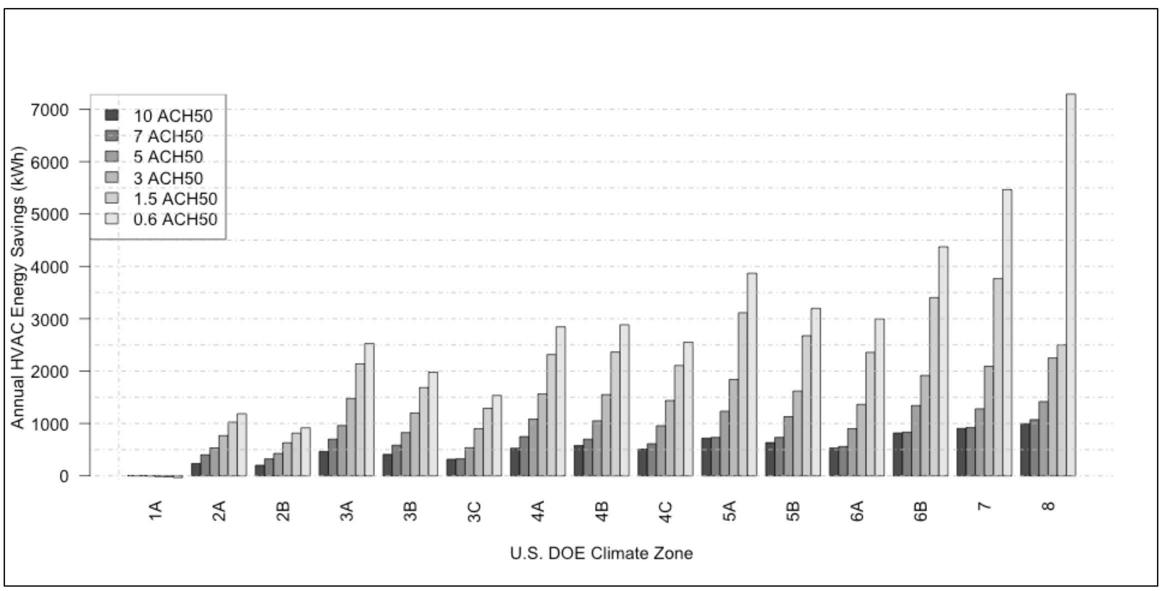


Figure 5 Single-story home with a single cut-off temperature at the 25th percentile lowest temperature of the year, based on TMY3 climate data. Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

3.3 Fan Re-Sizing for Equivalence

The cases discussed in the previous section were based on mechanical ventilation fans sized according to 62.2-2013, assuming a continuously operating fan. Once temperature control was applied, these systems became non-compliant with 62.2-2013, because annual relative exposure increased when the fans were turned off (see Table 11). This section summarizes the results of the fan re-sizing calculations performed using the Excel tool. The data and figures reported here only include those cases where fan size was increased and the increase was within the constraint of a 0.4 m^3/s (848 cfm) maximum fan size. The change in fan size is expressed as a multiplier of the original fan size or a Fan Size Multiplier (FSM). Summaries of changes in fan airflow, FSMs and initial 62.2-2013 fan airflows are provided for all test cases in Appendix 3.

In the majority of cases, FSMs were between 1.0 and 2.0 (0-10 l/s). The median upsizing factor across all homes that increased fan size was 1.22 (equivalent to about 5 l/s or 20% additional fan air flow). FSMs varied most strongly with airtightness, climate zone and cut-off type. Infiltration independent cut-off temperatures (i.e., 5°C and Q25th) led to the higher average upsizing factors than infiltration-dependent cut-offs. In general, fan upsizing factors were largest in the most airtight homes and in the most severe climate zones, as shown in Figure 6 and Figure 7. Climate zone 1 would appear to contradict this statement due to its large median FSM (1.6), but this was due to the fact that only the Q25th control strategy operated in this climate zone, and its upsizing factors were on average the largest. On average, upsizing factors did not differ by number of stories or house age. Though interactions between factors occurred in some cases, such as the relationship between airtightness and house age shown in Figure 8, where substantial differences occurred between new and existing types, but only in the most airtight test cases.

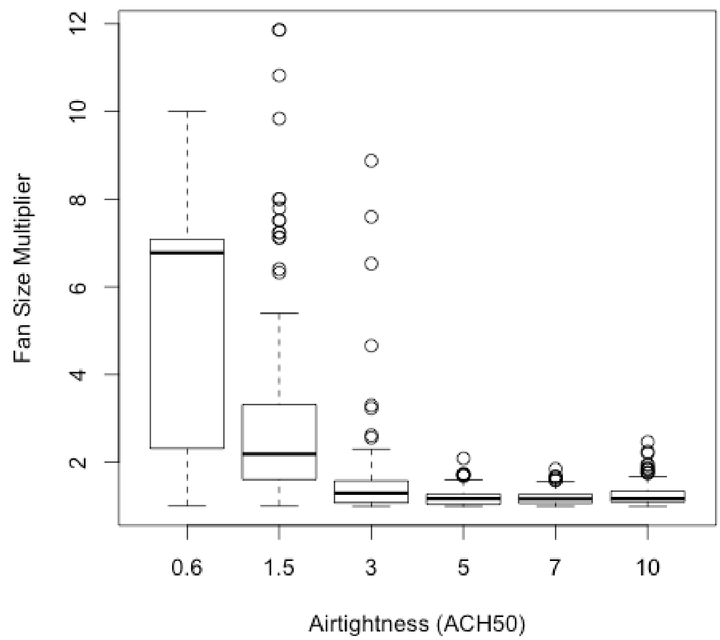


Figure 6 Summary of fan size multipliers aggregated by airtightness. Includes cases where fan size was increased and the increase was within the constraint of a 0.4 m^3/s (848 cfm) maximum fan size.

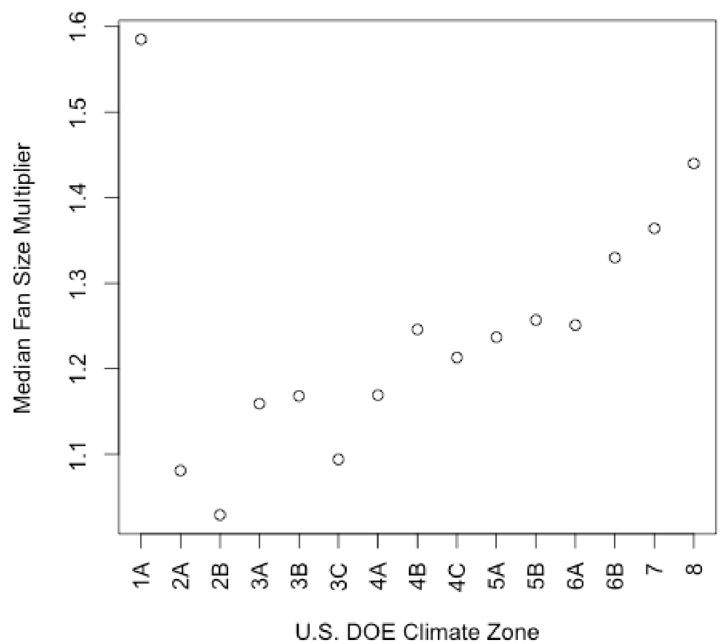


Figure 7 Median FSMs for each DOE climate zone. 1A has high average factors, because those cases that increased fan size were limited to Q25th cases, with higher average factors. Includes cases where fan size was increased and the increase was within the constraint of a 0.4 m^3/s (848 cfm) maximum fan size.

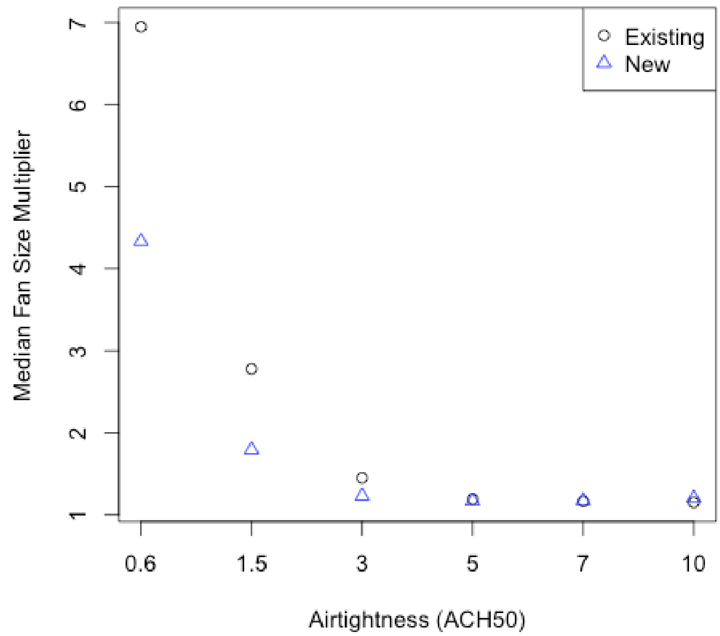


Figure 8 Median FSMs in new and existing home test cases aggregated by airtightness level. Includes cases where fan size was increased and the increase was within the constraint of a 0.4 m^3/s (848 cfm) maximum fan size.

3.4 Results Using Fans Resized to Better Achieve Equivalence

In all cases, increasing the fan size to achieve equivalence and compliance with 62.2-2013 led to lower energy reductions than were found using the initial fan sizes, as predicted by REGCAP simulations. With some exceptions, reductions in energy savings were modest. In many cases, reductions were entirely eliminated or drastically reduced, due to failure to reach equivalence or to massive fan upsizing that increased energy consumption during periods of fan operation. For those cases where reductions were not eliminated, increasing the fan sizes to achieve equivalence and compliance with 62.2-2013 reduced energy savings by between approximately 10% and 15%. Cases not reaching equivalence included 0.6 ACH_{50} in CZ3-8 and 1.5 ACH_{50} in CZ 6-8. The cases of dramatically reduced savings were 1.5 ACH_{50} in CZ 3-5.

Total energy reductions with oversized fans were highly variable depending on the home age (new vs. existing), control strategy, climate zone, airtightness and fan upsizing factor. For example, the results using two infiltration cut-offs are shown in Figure 9. Within CZ 2 to 8, energy savings were reduced as airtightness increased, and energy savings increased with increasing climate severity. Climate zone 1 was an exception, as savings from the Inf2 strategy were negligible for all airtightnesses. For infiltration based cut-offs, energy reductions in new homes were generally greater than in existing homes, because higher Q_{tot} values in existing homes lowered the cut-off temperatures, which reduced the number of annual hours the fans were turned off. This was often the opposite with infiltration-independent cut-offs, where fans were larger in existing homes due to higher target ventilation rates for existing homes in ASHRAE 62.2. These larger fans were turned off for the same number of hours as in the new home test cases, because infiltration independent cutoffs did not vary with airtightness or house age. Total annual energy savings, annual changes in AER and annual relative exposure are summarized for the other three temperature control strategies in Appendix 4. Total energy savings are provided individually for all test cases in Appendix 4.

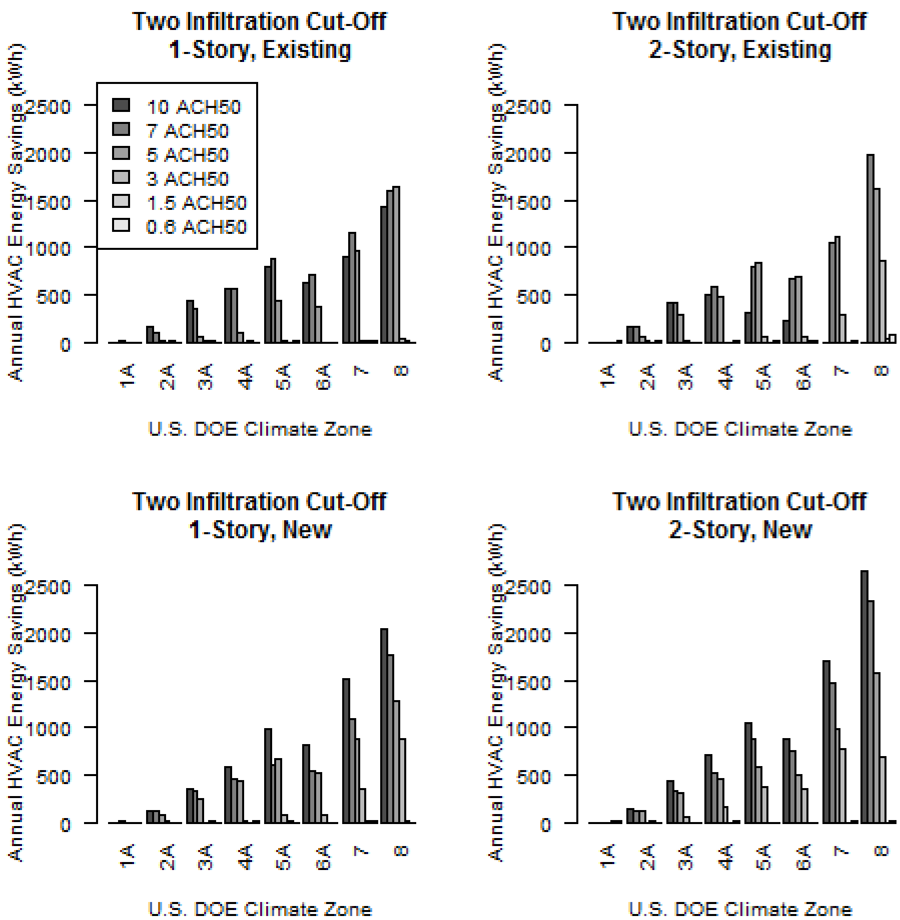


Figure 9 Summaries of total HVAC energy savings resulting from temperature-controlled ventilation, using two infiltration based cut-offs.

3.5 Performance of Recommended Cut-Off Strategies

We can offer no single recommendation for which of the four temperature cut-off types is best because energy reduction estimates varied by cut-off temperature type and by house and climate parameters,. Therefore, recommendations for the best temperature control strategy for any given scenario were based on the highest energy savings. We determined which of the four cut-off types (Inf, Inf2, 5°C or Q25th) provided the greatest savings for each of 192 test cases. The important factors in this analysis are airtightness, climate, age and number of stories. So, we grouped four test case groups by house age (new vs. existing) and number of stories (one vs. two), and we present our results and recommendations for cut-off types by airtightness and climate zone. This is done for the individual test groups and for a combination of the four test groups averaged together for which median values are reported.

Appendix 4 provides the energy savings for each of the four strategies in each test case and highlights the best cut-off strategy. Appendix 4 also summarizes the recommended cut-off type and the associated 62.2-2013 fan airflow, fan size multiplier, energy savings, and changes in relative exposure and AER, as well as cut-off temperature for each test case.

Maximum Energy Savings

The maximum energy reduction estimates (kWh and percentages) are provided for each individual test case in Table 12 organized by test group. The maximum energy savings estimates are shown as absolute (kWh) and percentage reductions in Figure 10 and Figure 11, respectively. These represent the highest energy reductions for the control strategies we assessed. Absolute energy reductions increased as climates became more severe (with the exception of a consistent, small drop in savings from climate 5A to 6A), and reductions were generally the greatest in the 3 and 5 ACH_{50} cases (in any given climate zone). Percentage savings were more consistent across climate zones, with less variability between zones 2 through 8. The highest savings in any given climate zone was almost always in the 3 or 5 ACH_{50} test cases. Both absolute and percentage energy savings were generally higher in existing homes, as characterized by test cases 10 through 5 ACH_{50} (exceptions were the leakiest homes in coldest climates, where no fan was required by 62.2 in an existing home). This was most likely due to higher fan airflows required in existing homes, and turning off larger fans saves more energy. Savings were sometimes highly variable between test groups, particularly in cases such as leaky, severe climate cases, where a fan was not specified in an existing home (i.e., CZ8, 10 ACH_{50}, existing, 2-story).

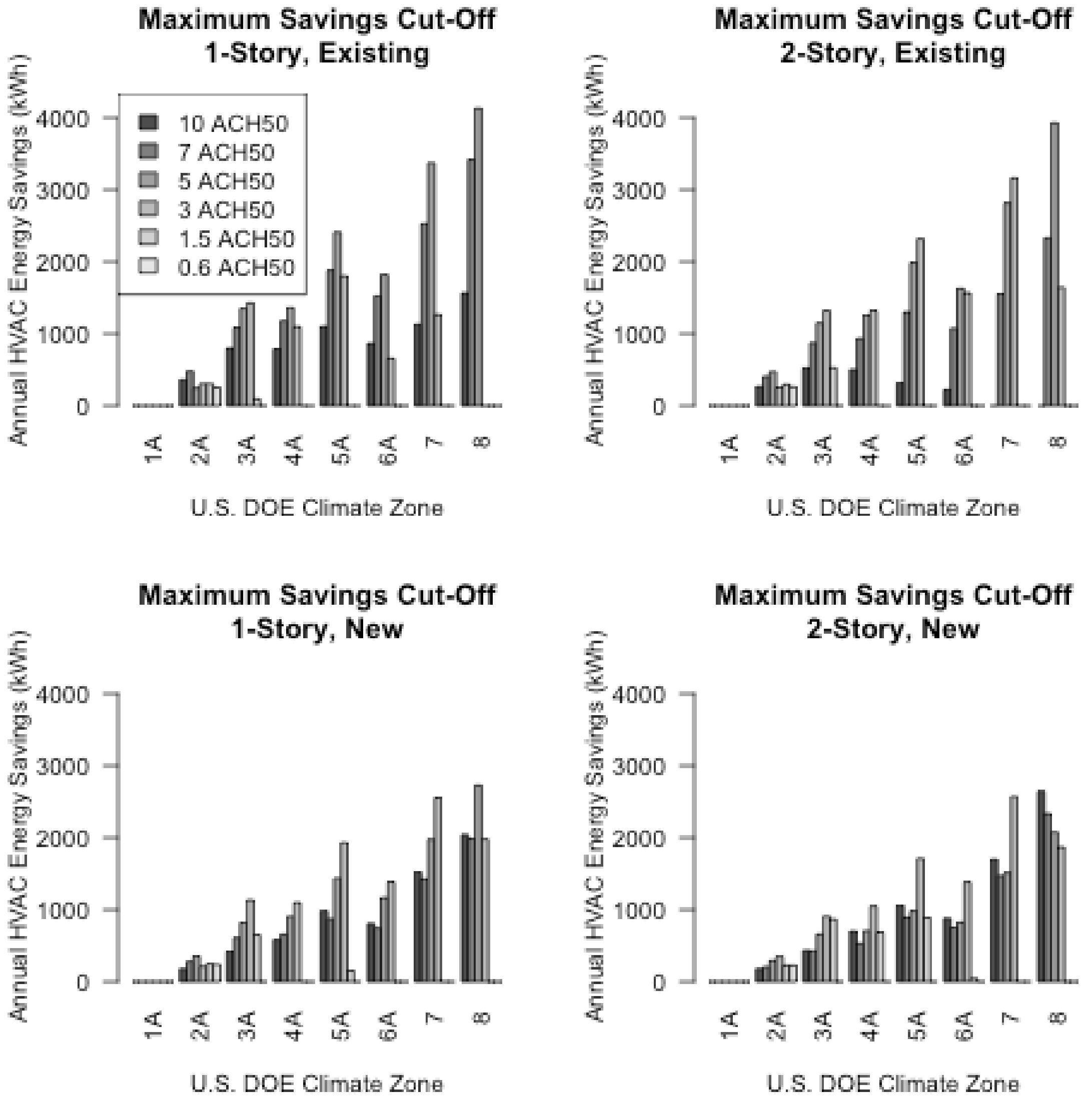


Figure 10 Estimated maximum HVAC energy reductions for each of four test groups (existing and new, 1- and 2-story).

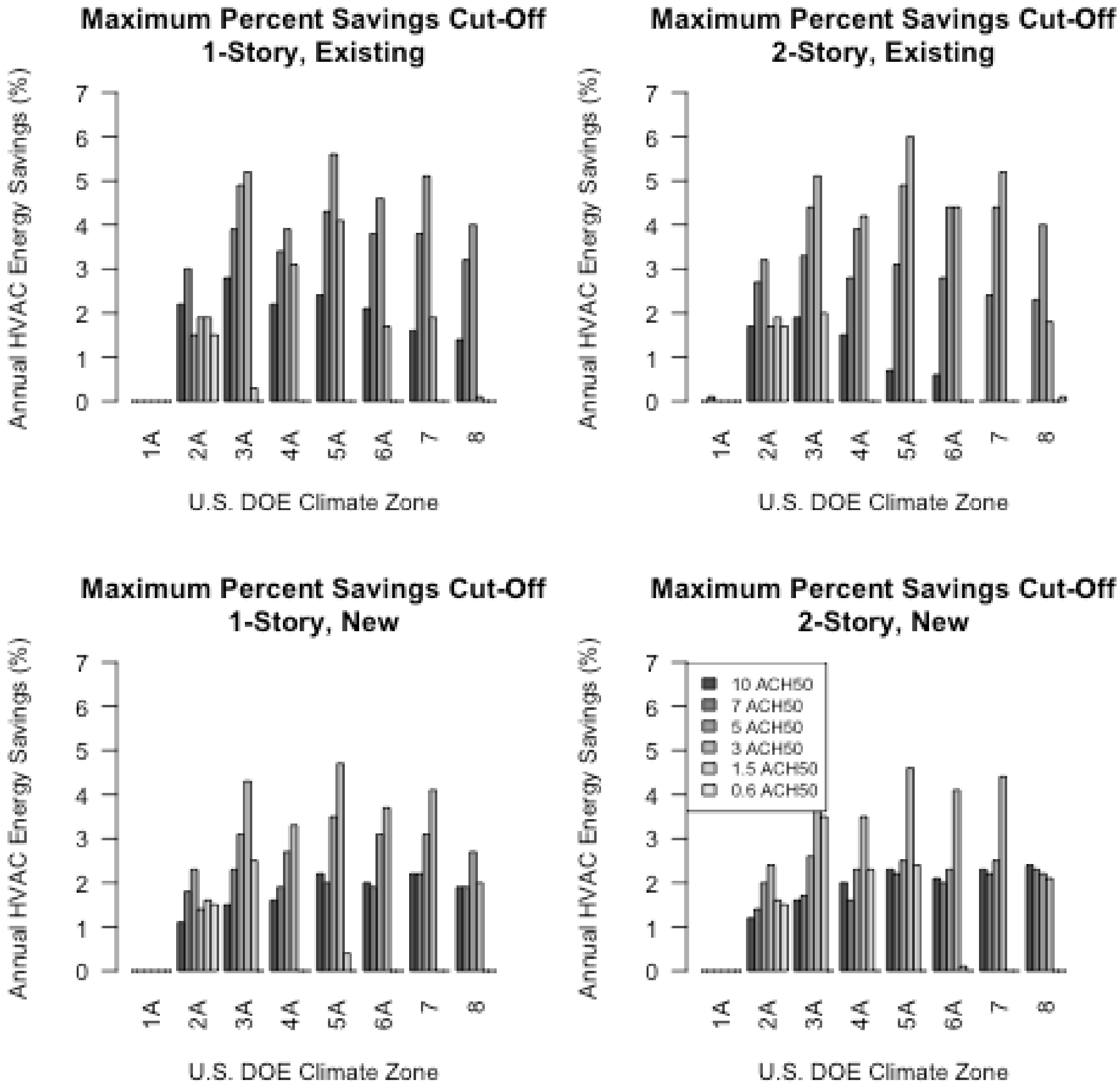


Figure 11 Estimated maximum HVAC percentage energy reductions for each of four test groups (existing and new, 1- and 2-story).

U.S. DOE Climate Zone	Maximum Estimated HVAC Energy Reduction (kWh) for Each Test Case					
	10 ACH_{50}	7 ACH_{50}	5 ACH_{50}	3 ACH_{50}	1.5 ACH_{50}	0.6 ACH_{50}
	Existing, 1-Story					
1A	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2A	359 (2.2%)	479 (3%)	245 (1.5%)	306 (1.9%)	305 (1.9%)	250 (1.5%)
3A	798 (2.8%)	1084 (3.9%)	1349 (4.9%)	1424 (5.2%)	90 (0.3%)	0 (0%)
4A	785 (2.2%)	1178 (3.4%)	1359 (3.9%)	1095 (3.1%)	0 (0%)	0 (0%)
5A	1099 (2.4%)	1881 (4.3%)	2409 (5.6%)	1798 (4.1%)	0 (0%)	0 (0%)
6A	866 (2.1%)	1523 (3.8%)	1816 (4.6%)	657 (1.7%)	0 (0%)	0 (0%)
7	1125 (1.6%)	2527 (3.8%)	3372 (5.1%)	1262 (1.9%)	0 (0%)	0 (0%)
8	1565 (1.4%)	3417 (3.2%)	4128 (4%)	0 (0%)	0 (0%)	0 (0%)
	Existing, 2-Story					
1A	0 (0%)	0 (0.1%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2A	263 (1.7%)	404 (2.7%)	473 (3.2%)	254 (1.7%)	294 (1.9%)	258 (1.7%)
3A	523 (1.9%)	873 (3.3%)	1145 (4.4%)	1316 (5.1%)	526 (2%)	0 (0%)
4A	504 (1.5%)	932 (2.8%)	1255 (3.9%)	1317 (4.2%)	0 (0%)	0 (0%)
5A	316 (0.7%)	1299 (3.1%)	1983 (4.9%)	2314 (6%)	0 (0%)	0 (0%)
6A	223 (0.6%)	1073 (2.8%)	1624 (4.4%)	1567 (4.4%)	0 (0%)	0 (0%)
7	0 (0%)	1555 (2.4%)	2813 (4.4%)	3159 (5.2%)	0 (0%)	0 (0%)
8	0 (0%)	2326 (2.3%)	3926 (4%)	1638 (1.8%)	0 (0%)	0 (0%)

U.S. DOE Climate Zone	10 ACH_{50}	7 ACH_{50}	5 ACH_{50}	3 ACH_{50}	1.5 ACH_{50}	0.6 ACH_{50}
	New, 1-Story					
1A	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2A	176 (1.1%)	279 (1.8%)	353 (2.3%)	210 (1.4%)	248 (1.6%)	238 (1.5%)
3A	422 (1.5%)	611 (2.3%)	822 (3.1%)	1134 (4.3%)	650 (2.5%)	0 (0%)
4A	582 (1.6%)	656 (1.9%)	905 (2.7%)	1099 (3.3%)	0 (0%)	0 (0%)
5A	981 (2.2%)	869 (2%)	1437 (3.5%)	1931 (4.7%)	153 (0.4%)	0 (0%)
6A	807 (2%)	746 (1.9%)	1165 (3.1%)	1384 (3.7%)	0 (0%)	0 (0%)
7	1520 (2.2%)	1424 (2.2%)	1977 (3.1%)	2551 (4.1%)	0 (0%)	0 (0%)
8	2039 (1.9%)	1987 (1.9%)	2723 (2.7%)	1980 (2%)	0 (0%)	0 (0%)
	New, 2-Story					
1A	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
2A	177 (1.2%)	203 (1.4%)	293 (2%)	347 (2.4%)	224 (1.6%)	224 (1.5%)
3A	436 (1.6%)	427 (1.7%)	658 (2.6%)	908 (3.7%)	864 (3.5%)	0 (0%)
4A	699 (2%)	528 (1.6%)	704 (2.3%)	1046 (3.5%)	685 (2.3%)	0 (0%)
5A	1055 (2.3%)	890 (2.2%)	982 (2.5%)	1708 (4.6%)	887 (2.4%)	0 (0%)
6A	875 (2.1%)	753 (2%)	822 (2.3%)	1382 (4.1%)	41 (0.1%)	0 (0%)
7	1697 (2.3%)	1472 (2.2%)	1512 (2.5%)	2570 (4.4%)	0 (0%)	0 (0%)
8	2646 (2.4%)	2333 (2.3%)	2077 (2.2%)	1867 (2.1%)	0 (0%)	0 (0%)

Table 12 Maximum estimated HVAC energy reductions resulting from maximum savings control strategy for each of four test case groups (see table for recommended cut-off types in each case).

Recommended Cut-Off Temperature Strategies

The strategy that provided the maximum energy reduction (and the associated cut-off temperature and fan size multiplier) is indicated for each climate zone and airtightness level for each test case group in Table 13.

We would not recommend temperature-controlled ventilation in approximately 35% of the test cases (indicated as "None" in tables), due to one or more of the following: (1) failure to achieve equivalence, (2) required fan oversizing too great (i.e., >300 or 400 cfm), or (3) increased energy use or very low energy reductions (<50 kWh). Broadly speaking, this control strategy was not effective in climate zone 1, and it was generally not effective in the most airtight test cases (0.6 ACH_{50}). The single infiltration-dependent cut-off (Inf) was almost never the best strategy, because nearly all cases where Inf produced the maximum energy reductions were cases where predicted savings were very low. The 5°C cut-off provided the highest average savings for the largest number of test cases (~40% of test cases). This strategy worked best in moderately airtight homes (3 to 7 ACH_{50}), in more severe climates (4A+)[6], and worked equally well in new and existing cases. The two infiltration-dependent cut-offs (Inf2) was the next best strategy in terms of average maximum savings, but it was the best strategy in only a minority of test cases (~8%). Inf2 was generally the best performer in new, leaky homes (10 ACH_{50}, with only a couple 7 ACH_{50} cases), located in more severe climates (3+). $Q25^{th}$ provided lower average maximum savings, but it did so in more test cases (~20%). It was the best choice in moderately tight and leaky (3 ACH_{50}+) test cases located in climate zones 2 and 3.

We would like to highlight some limited cases where the best strategy is open to interpretation. We have recommended the cut-off type with the maximum energy savings, but in some of the Inf2 cases, the small incremental energy benefits may not justify the added complexity of multi-speed fan control. This occurs primarily in 1 and 2-story, new 10ACH_{50} homes, in which the best strategy could just as well be Inf (or 5°C) and not Inf2. In these cases, the average incremental energy benefit of going to Inf2 from the simpler Inf was only 117 and 44 kWh in 1- and 2-story cases, respectively. Not only would the fan technology and controls be more complex in Inf2, but the required fan oversizing is greater, which could lead to noise or space issues, as discussed in the fan sizing section below. For example, FSMs in these Inf2 cases were 16% and 18% greater than those in the respective Inf cases.

[6] Notably, in climate zone 4A, the cut-off temperatures and results in the 5°C and $Q25^{th}$ cases were identical. In these cases, the 5°C is indicated as the best strategy, but $Q25^{th}$ has the same results.

ACH_{50}	Age	Climate Zone	Cut-Off Type	FSM	Cut-Off Temperature (°C)	Cut-Off Type	FSM	Cut-Off Temperature (°C)
			1-Story			2-Story		
10	existing	1A	None	None	None	None	None	None
10	existing	2A	Q25th	1.29	15	Q25th	1.26	15
10	existing	3A	Q25th	1.19	9.4	Q25th	1.16	9.4
10	existing	4A	5C	1.15	5	Inf2	1.24	2.6 / 13.8
10	existing	5A	5C	1.25	5	5C	1.19	5
10	existing	6A	5C	1.28	5	Inf2	1.39	2.6 / 13.8
10	existing	7	5C	1.38	5	None	None	None
10	existing	8	5C	1.45	5	None	None	None
7	existing	1A	None	None	None	None	None	None
7	existing	2A	Q25th	1.31	15	Q25th	1.29	15
7	existing	3A	Q25th	1.21	9.4	Q25th	1.2	9.4
7	existing	4A	5C	1.19	5	5C	1.17	5
7	existing	5A	5C	1.34	5	5C	1.28	5
7	existing	6A	5C	1.37	5	5C	1.32	5
7	existing	7	5C	1.56	5	5C	1.44	5
7	existing	8	5C	1.68	5	5C	1.53	5
5	existing	1A	None	None	None	None	None	None
5	existing	2A	5C	1.04	5	Q25th	1.33	15
5	existing	3A	Q25th	1.28	9.4	Q25th	1.22	9.4
5	existing	4A	5C	1.25	5	5C	1.2	5
5	existing	5A	5C	1.44	5	5C	1.36	5
5	existing	6A	5C	1.51	5	5C	1.4	5
5	existing	7	5C	1.72	5	5C	1.6	5
5	existing	8	5C	2.09	5	5C	1.74	5
3	existing	1A	None	None	None	None	None	None
3	existing	2A	5C	1.07	5	5C	1.05	5
3	existing	3A	Q25th	1.76	9.4	Q25th	1.42	9.4
3	existing	4A	5C	1.66	5	5C	1.37	5
3	existing	5A	Q25th	1.51	1.1	5C	1.67	5
3	existing	6A	Q25th	1.5	-0.6	5C	1.82	5
3	existing	7	Q25th	1.37	-5	5C	2.23	5
3	existing	8	None	None	None	Q25th	1.24	-14.4
1.5	existing	1A	None	None	None	None	None	None
1.5	existing	2A	5C	1.12	5	5C	1.1	5
1.5	existing	3A	5C	1.73	5	5C	1.48	5
1.5	existing	4A	None	None	None	None	None	None

1.5	existing	5A	None	None	None	None	None	None
1.5	existing	6A	None	None	None	None	None	None
1.5	existing	7	None	None	None	None	None	None
1.5	existing	8	None	None	None	None	None	None
0.6	existing	1A	None	None	None	None	None	None
0.6	existing	2A	5C	1.16	5	5C	1.15	5
0.6	existing	3A	None	None	None	None	None	None
0.6	existing	4A	None	None	None	None	None	None
0.6	existing	5A	None	None	None	None	None	None
0.6	existing	6A	None	None	None	None	None	None
0.6	existing	7	None	None	None	None	None	None
0.6	existing	8	None	None	None	None	None	None
10	new	1A	None	None	None	None	None	None
10	new	2A	Q25th	1.25	15	Q25th	1.24	15
10	new	3A	Q25th	1.16	9.4	Inf2	1.3	9.2 / 16.2
10	new	4A	Inf2	1.29	4.2 / 14.4	Inf2	1.42	9.2 / 16.2
10	new	5A	Inf2	1.43	4.2 / 14.4	Inf2	1.63	9.2 / 16.2
10	new	6A	Inf2	1.52	4.2 / 14.4	Inf2	1.83	9.2 / 16.2
10	new	7	Inf2	1.77	4.2 / 14.4	Inf2	2.25	9.2 / 16.2
10	new	8	Inf2	1.93	4.2 / 14.4	Inf2	2.47	9.2 / 16.2
7	new	1A	None	None	None	None	None	None
7	new	2A	Q25th	1.29	15	Q25th	1.27	15
7	new	3A	Q25th	1.19	9.4	Q25th	1.17	9.4
7	new	4A	5C	1.16	5	Inf2	1.25	1.6 / 13.5
7	new	5A	5C	1.27	5	5C	1.25	5
7	new	6A	5C	1.3	5	5C	1.29	5
7	new	7	5C	1.46	5	5C	1.43	5
7	new	8	5C	1.56	5	Inf2	1.85	1.6 / 13.5
5	new	1A	None	None	None	None	None	None
5	new	2A	Q25th	1.3	15	Q25th	1.29	15
5	new	3A	Q25th	1.21	9.4	Q25th	1.2	9.4
5	new	4A	5C	1.19	5	5C	1.17	5
5	new	5A	5C	1.34	5	5C	1.29	5
5	new	6A	5C	1.38	5	5C	1.33	5
5	new	7	5C	1.56	5	5C	1.49	5
5	new	8	5C	1.69	5	5C	1.6	5
3	new	1A	None	None	None	None	None	None
3	new	2A	5C	1.04	5	Q25th	1.37	15
3	new	3A	Q25th	1.36	9.4	Q25th	1.25	9.4
3	new	4A	5C	1.31	5	5C	1.23	5
3	new	5A	5C	1.58	5	5C	1.41	5

3	new	6A	5C	1.69	5	5C	1.46	5
3	new	7	5C	2.02	5	5C	1.66	5
3	new	8	Q25th	1.22	-14.4	5C	1.93	5
1.5	new	1A	None	None	None	None	None	None
1.5	new	2A	5C	1.08	5	5C	1.07	5
1.5	new	3A	5C	1.4	5	Q25th	1.82	9.4
1.5	new	4A	None	None	None	5C	1.76	5
1.5	new	5A	Q25th	2.22	1.1	Q25th	1.61	1.1
1.5	new	6A	None	None	None	Q25th	1.61	-0.6
1.5	new	7	None	None	None	None	None	None
1.5	new	8	None	None	None	None	None	None
0.6	new	1A	None	None	None	None	None	None
0.6	new	2A	5C	1.12	5	5C	1.11	5
0.6	new	3A	None	None	None	None	None	None
0.6	new	4A	None	None	None	None	None	None
0.6	new	5A	None	None	None	None	None	None
0.6	new	6A	None	None	None	None	None	None
0.6	new	7	None	None	None	None	None	None
0.6	new	8	None	None	None	None	None	None

Table 13 Summary of recommended cut-off types, cut-off temperatures and fan size multipliers (FSM), based on having provided the highest energy reductions of the four strategies tested.

Fan Oversizing, Air Exchange Rates and Relative Exposure

Median fan oversizing in these recommended cases was 1.29 (8 L/s) (mean 1.34; 11 L/s), with minimum and maximum FSMs of 1.04 (1 L/s) and 2.47 (50 L/s), respectively. FSMs are provided for each maximum savings test case in Table 13. FSMs generally were smallest in climate zones 3 or 4 and then increased as climate severity increased (consistent with Figure 7 above).

There is a practical limit to fan oversizing in terms of the realistic ability to install a fan of higher capacity. This includes spatial limits on duct sizing, as well as the availability of fans with sufficient air flow that meet other requirements, such as noise or space constraints. A reasonable limit would be a factor of two or less in oversizing, though this will depend largely on the initial size of the 62.2 fan, which varies substantially by airtightness and climate zone. 97% of the recommended oversized fans in Table 13 meet this limit. Another option might be to have more than one fan that would bypass size and space limits, but this comes with other issues such as increased cost, more complex controls and potentially limited availability of a suitable location for a second fan. Air exchange rates and relative exposure are intricately connected, but whereas the AER is a simple arithmetic mean over the course of the year, the exposure reflects the effects of time-varying ventilation. Our results suggest that temperature controlled ventilation that maintains equivalence with 62.2-2013 can either lead to increased or decreased annual average AER.

For the cut-off strategies we recommend, the median of the absolute values of the AERs was 0.005 hr^{-1}, reflecting an average change on the order of 1%. AERs were generally reduced in leakier homes (i.e., 5 to 10 ACH_{50}) and were increased in the more airtight test cases where we recommend temperature control. Median changes in AERs were substantially different in cases where AERs increased versus decreased. The median decrease in AERs was 0.0086 hr^{-1}, and the median increase in AERs was 0.020 hr^{-1}.

Despite this variability in AERs, exposure was either reduced (or increased by 1% or less) in all of our recommended ventilation control strategies. The median decrease in exposure in new test cases was 1%. Overall, this suggests that our simplified Excel-based method for fan oversizing and maintaining equivalence is robust and effective. Nevertheless, there was substantial variability between our method's predictions and the results of the complex REGCAP model. There were only three cases out of 768[7] where our simplified method predicted equivalence and it was not achieved in the REGCAP simulations. There were a number of cases where exposure was actually reduced much further than is required for equivalence to 62.2-2013 (i.e., from 5% to 17% reductions). These were almost entirely in airtight homes (i.e., 0.6, 1.5 and 3 ACH_{50} test cases). This is consistent with our finding of larger increases in AERs in airtight homes. While these reductions in exposure are good from a pollutant exposure perspective, they do suggest that the fan was larger than necessary and energy savings could have been greater with a more appropriately oversized fan. This may reflect a weakness of our fan oversizing method in homes 3 ACH_{50} or less.

The main drivers of this variability were: (1) the simplification of air exchange calculations in the Excel sheet (i.e., infiltration and superposition), and (2) the presence of duct leakage in the REGCAP model (assumed to be 6% in our simulations). As fan size and timing of fan operation were varied, so to were HVAC system runtimes and associated duct leakage. This led to particularly odd results in the cases where large fans were required for equivalence. These large fans led to massive increases in energy use (50% to 100% increases), and duct leakage similarly increased, which had a large impact on air exchange and exposure. Most of these cases actually had large reductions in exposure, which we suspect resulted from the additional duct leakage. This interactive effect of duct leakage also affected the more typical cases. For example, when energy use was decreased, so to was air exchange through duct leaks, which might increase exposure in cases of fan control.

[7] 5 ACH_{50} 1-story existing CZ 2A ($Q25^{th}$), and 3 ACH_{50} 2-story existing and 1-story new cases in CZ 2A ($Q25^{th}$). The latter two almost met the 1% increased exposure threshold.

In these cases, changes in system runtime would be expected to be much smaller, as energy savings were small compared with the 50-100% energy use increases reported above. In fan oversizing calculations, we think that duct leakage should not be given credit and allowed to offset the ventilation required through the 62.2 fan, but it is important to know that it has substantial effects on air exchange and that it interacts dynamically with ventilation control strategies in the real world.

3.6 Relation of Cut-Off Temperature to Energy Savings

Ultimately, our recommendations bear out our earlier hypothesis that, within the constraint of providing equivalence, higher cut-off temperatures would lead to higher energy savings. Figure 12 illustrates the varying relationship between cut-off temperature and estimated energy savings. These values reflect only 2-story, new homes in climate zone 7, but they show the consistent positive correlation between higher cut-offs and higher savings in 3 to 10 ACH_{50} test homes. This suggests that in some cases, higher cut-off temperatures than those evaluated in this study may be able to achieve even greater energy savings, while maintaining equivalence with 62.2-2013.

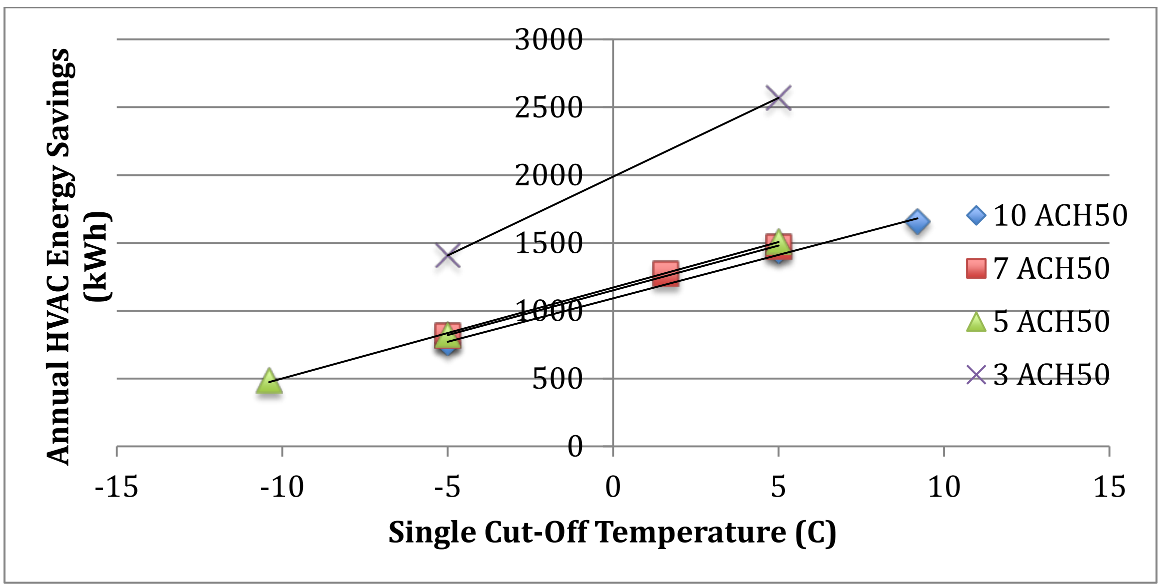


Figure 12 Example of the variance of energy savings with cut-off temperature, 2-story, new homes in climate zone 7. Energy savings increase with higher cut-offs. Within this range of airtightness and cut-offs, no decay is observed.

This relationship is not always so consistent. For example, in 1-story new test cases in climate zone 8, the positive correlations remain for 10, 7 and 5 ACH_{50} homes, but the 3 ACH_{50} home experiences a severe deadening of the effect, such that going from a -14°C cut-off ($Q25^{th}$) up to a 5°C cut-off has almost no effect on energy savings (increases savings by only 65 kWh). But the 5°C strategy requires a 223% increase in fan airflow to be equivalent, whereas the $Q25^{th}$ method requires only a 22% oversizing. In this case, we recommend $Q25^{th}$, to avoid difficult-to-implement fan oversizing that provides little benefit. We expect that at temperature cut-offs even higher than 5°C, fan oversizing and equivalence requirements would in fact lead to increased energy use in 1-story, new 3 ACH_{50} cases in climate zone 8. This illustrates the dynamic way in which cut-off temperature, airtightness and relative exposure interact and can produce unexpected results, particularly in more airtight homes.

These results suggest that a method should be developed for determining the highest appropriate cut-off temperature (subject to the equivalence requirement) for each combination of airtightness and climate zone. The excel tool described in the Methods section could be used to identify optimal temperatures, when given a pre-specified fan size. An example of results for climate zone 5A is provided in Table 14, using a fixed 50% fan over sizing factor (FSM of 1.5). The optimum temperature cut-offs are compared with those used in our maximum savings cases from this report. In 3, 5 and 7 ACH_{50} cases, we recommended 5°C cut-offs based on our results, but higher temperatures, as specified in Table 14, could have yielded higher savings. In these cases, the FSMs in our simulations were less than 1.5. Conversely, in the 1.5 ACH_{50} case, we recommended 1.1°C ($Q25^{th}$), which is a higher temperature than in Table 14 (with more savings), and accordingly the FSM used in our simulations was greater than 1.5 (1.6). Fan over sizing and temperature cut-offs varied substantially with house and climate parameters. As a result, it is most likely that a useful application of this control strategy would include user-specified fan airflow, and a tool that would calculate a custom temperature cut-off, given the specific house and climate characteristics.

While performing these examples in the Excel tool, we observed that poorer optimizations were achieved in terms of relative exposure and equivalence. As a result, this method may need further refinement. In the meantime, our simplified recommendations above provide robust savings across climate zones and levels of airtightness.

ACH_{50}	Fixed FSM	Optimal Cut-Off Temp (°C)	Maximum Savings FSM	Maximum Savings Cut-Off (°C)
10	1.5	11.7	1.63	9.2 / 16.2 (Inf2)
7	1.5	10.8	1.25	5 (5°C)
5	1.5	9.0	1.29	5 (5°C)
3	1.5	6.4	1.41	5 (5°C)
1.5	1.5	0.6	1.61	1.1 ($Q25^{th}$)

Table 14 Example of optimal cut-off temperature calculations for a 2-story, new test case in climate zone 5A, assuming a consistent 50% over sizing.

3.7 Caveats and Limitations

There are several caveats associated with our results. The realized energy savings will change with other variables not thoroughly evaluated in this study. For example, more or less efficient heating or cooling systems would change the energy savings—roughly in proportion to the differences between the efficiencies assumed in this analysis and those of the particular home under study. System efficiency would also affect runtime, with its associated effects on air exchange and exposure noted above. Similarly, varying duct leakages were not assessed. This is of particular note given that the impact of duct leakage, even in a relatively airtight system (6% leakage) was substantial. Local weather conditions can vary from the representative values used in the TMY data, which could result in either more or less time with ventilation control turning the fan off. Energy savings, air exchange and exposure will also vary with the type of ventilation system, particularly as balanced ventilation systems deliver higher levels of air exchange than their unbalanced counterparts. Furthermore, ERV/HRV may have lower ventilation loads than the exhaust only systems simulated in this study, and as a result, their energy savings from fan control will likely be lower. Finally, larger or smaller homes will see proportionally greater and smaller energy savings. However, we do not expect that our recommendations of cut-off type will vary with home size in most cases (exceptions are noted in the Methods section). This is because the relative exposure and energy savings used in the selection of cutoff are relative to a base case, and all these factors also change the base case. This minimizes their effect on choice of cutoff strategy.

In addition, further constraints on the simple temperature control strategy were not investigated. For example, no acute exposure limits were put in place. As long as an oversized fan was able to achieve equivalence over the course of a full year, then short-term exposure was allowed to climb without limit. The 62.2-2013 standard establishes no limit for short-term exposure, but Sherman, Logue & Singer (2011) have suggested that 2.5 is a protective (i.e., highly conservative) 24-hour exposure limit, based upon comparisons of simulated pollutant concentrations of acute and chronic exposures (M. H. Sherman, Logue, & Singer, 2011). In this research, fans were turned off for substantial, uninterrupted periods, and there is concern that short-term pollutant levels may have become unacceptable at times. We expect this issue to be greatest in airtight homes, where infiltration is minimal when the fan is turned off. We examined this potential issue and found little reason for concern. For example, one-minute exposure values are shown in time series in Figure 13 for a 1.5 ACH_{50}, 1-story, new home in CZ 2A using a 5°C cut-off. The 24-hour exposure limit of 2.5 (red line) is shown for reference, and even the one-minute exposure values in this airtight home exceeded the threshold for mere minutes out of the year. Examples from leakier homes showed even less cause for concern. This suggests that this issue is not of concern in our recommend cases. But if a $Q25^{th}$ cut-off was used in a 1.5 ACH_{50} home in climate zone 2A (not recommended), then the exposure limit of 2.5 would be regularly exceeded during cold seasons. While it does not appear to be a concern in most cases, if desired, a high-end limit for relative exposure could be used in a controller, which would recommence fan operation no matter what the outside temperature. Even more simply, the fan could be made to operate for a fixed period every day, no matter what the outside temperature (e.g., 4-hours of daily operation, late in the afternoon). While these additional constraints may seem like they would reduce energy savings, it is possible that they might actually increase them, because the fan oversizing requirements would be less. Future work should investigate the effects of such additional constraints.

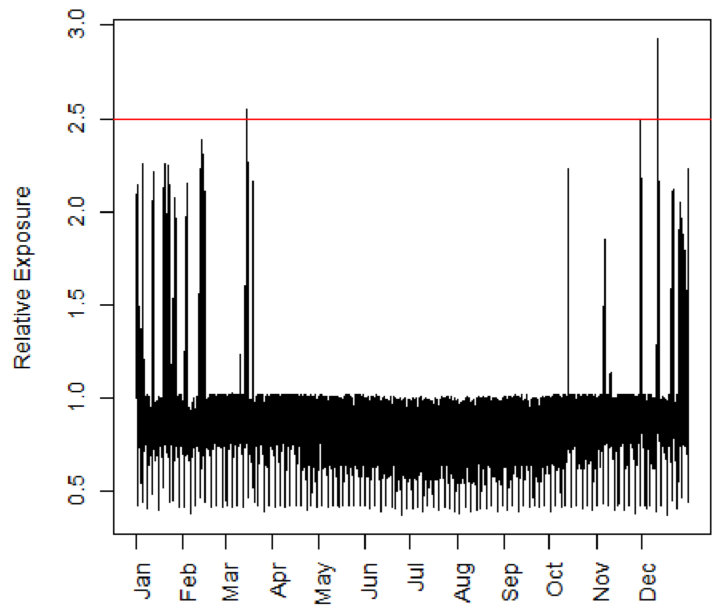


Figure 13 Example of one-minute exposure calculations in a 1.5 ACH_{50}, 1-story, new test case located in climate zone 2A using a 5°C cut-off. No upper exposure limit was used in this example, and the highly conservative 2.5 exposure threshold (horizontal red line) was exceeded for no more than a handful of minutes per year.

Finally, we noted substantial differences in the fan oversizing calculations, depending on the method of superposition employed (quadrature vs. half-linear), and our fan oversizing appeared to be too aggressive in more airtight test cases. More research is required to determine which superposition method is best at calculating fan oversizing for any given control type. For example, temperature controlled ventilation turns off the ventilation fan during periods with large temperature differences. Potentially the half-linear method provides better estimates of changes in air exchange due to fan control under these conditions. But if a ventilation control strategy was being used that was independent of outside temperature, such as timer-based controls, then maybe quadrature would provide better estimates of the effects of turning off the fan. This work is especially important as ventilation control is incorporated into energy codes, rating systems and simplified simulation engines (e.g., HERS rating software).

4 Guidance for Use of Temperature Controlled Ventilation

This report documents the potential energy savings and IAQ impacts of temperature controlled ventilation that maintains equivalence with a continuous fan sized according to 62.2-2013. At present, if a user wants to implement temperature-controlled ventilation that maintains equivalence with 62.2-2013 consistent with our methods in this report, we recommend the following process:

1. Calculate the fan airflow requirement from 62.2-2013, including an infiltration adjustment and existing home airflow deficits (if applicable);
2. Identify the appropriate test case (i.e., combination of house age, airtightness, climate zone and number of stories) (see footnotes about house age[8] and floor area[9]);
3. Lookup the fan size multiplier (FSM) and cut-off temperature for the applicable test case in Table 13 and multiply the 62.2-2013 fan airflow rate from Step 1 by this FSM to generate a new, higher fan airflow requirement;
4. Use a temperature sensor, thermostat and relay (or other controller) to turn this oversized fan off at the recommended cut-off temperature.

This approach reflects reasonably robust guidance as to fan sizing and cut-off temperature strategies. Nevertheless, it is clear that a more customized solution is appropriate, which can account for the specifics of any given home, namely varying floor area, flow deficits (in existing homes), airtightness, etc. In the residential market, an outdoor temperature ventilation controller would most likely work in such a customized way, as follows:

1. Calculate the fan airflow requirement from 62.2-2013, including an infiltration adjustment and existing home airflow deficits (if applicable);
2. Install and measure the fan airflow (must be larger than 62.2 requirement from Step 1) and calculate the Fan Size Multiplier (ratio of installed-to-required airflow);
3. The user would use a tool into which they would enter information about the house and the ventilation fan (airtightness, number of stories, climate zone, 62.2-2013 Q_{tot} flow requirement and the FSM calculated in Step 2);
4. The tool would automatically generate a recommended, optimal cut-off temperature that maintains equivalence with 62.2-2013.

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[8] Our existing home cases assume a flow deficit of 65 L/s. Only use values provided in Table 13 if the actual flow deficit in your project is substantially similar. Other users will have to wait until a custom tool is available.

[9] This report has summarized some example calculations for a fixed house size of 195 m^2 (see Table 13), in select climate zones. But how can users proceed with our guidance in either larger or smaller homes? We performed some example fan sizing calculations (assuming 5°C cut-off in climate zone 5A) in homes of varying sizes, and we found that FSMs varied significantly only in cases 3 ACH_{50} and tighter. In leakier cases, simply applying the FSMs we provide in this report is an adequate approach. In tighter homes smaller than 195 m^2, users should not use the FSM in Table 13 as exposure will increase. We do not recommend this strategy in such cases, until a custom tool is available. Larger airtight homes (3 ACH_{50} and less) can use the FSMs in Table 13 and maintain equivalence, but energy savings are expected to be reduced.

Unfortunately, no such tool currently exists on the market. It could be integrated into existing simulation tools (e.g., BEopt or Energy Gauge), or it could be part of a stand-alone application.

5 Conclusions

In 3 to 10 ACH_{50} test homes, substantial energy savings have been shown to result from the smart control of ventilation systems based on outdoor temperature, while maintaining equivalence with ASHRAE 62.2-2013 through fan oversizing. Limited savings were realized in milder climates for tighter homes. Energy reductions generally increased with climate severity, and in nearly all cases, they were greatest in airtightnesses 3 and 5 ACH_{50}. Simulations demonstrated annual HVAC energy savings ranging from approximately 100 kWh to 4,000 kWh. Using a sequential optimization tool, fans were oversized by an average of 34% (ranging from approximately 5% to 150%), and equivalence with 62.2-2013 was maintained in all of these cases. Temperature controlled ventilation is not recommended in climate zone 1 or in most of the very airtight cases (i.e., 1.5 and 0.6 ACH_{50}).

As a general guiding principle, energy savings increased with reductions in mechanical fan runtime, resulting from higher cut-off temperatures. These reductions in runtime required larger fan sizes in order to maintain equivalence with 62.2. This dynamic was not consistent in more airtight homes, where higher cut-off temperatures often necessitated substantially larger fans to maintain equivalence, which led to increased HVAC energy use. The simplest strategy (a 5°C cut-off) was in fact the most effective across a variety of climate zones, though it was not effective in all cases where savings were identified.

Our guidance for temperature control strategies is robust, though not optimal, as higher cut-offs with higher energy savings can be calculated. We recommend that tools be developed to calculate the best temperature cut-offs for varying airtightnesses and climate zones. Furthermore, this was a narrow investigation of smart ventilation control based on outdoor temperature, and while we make recommendations within this realm, there may be other smart ventilation strategies that are lower cost, more robust or more effective. For example, a more simple timer-based control could also be used to selectively not ventilate during the coldest periods of any given day, and this would require no temperature sensor and would eliminate the complex process of calculating cut-off temperatures and fan sizes.

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A. Appendix 1 Methods for Adding Fan Airflows to Natural Infiltration

As discussed in the fan oversizing section of the report, both the Quadrature and the Half-Linear methods of combining mechanical and natural infiltration were used in the Excel-based fan re-sizing processes (see Equation A-6 and Equation A-7). This was done in order to identify differences and the relative accuracy of the two methods. This discussion is specific to the case of ventilation controlled by outdoor temperature.

$$Q_{comb} = Q_{bal} + \sqrt{Q_{unbal}^2 + Q_{infiltration}^2}$$

Q_{comb} = combined total airflow, L/s
Q_{bal} = balanced mechanical airflow, L/s
Q_{unbal} = unbalanced mechanical airflow, L/s
$Q_{infiltration}$ = infiltration natural airflow, L/s

Equation A-1 Quadrature method for combining mechanical ventilation and infiltration airflows.

$$If\left(Q_{unbal} < 2 \times Q_{infiltration}\right)$$
$$Q_{comb} = Q_{infiltration} + \frac{Q_{unbal}}{2}$$
$$Else$$
$$Q_{comb} = Q_{unbal}$$

Q_{comb} = combined total airflow, L/s
Q_{unbal} = unbalanced mechanical airflow, L/s
$Q_{infiltration}$ = infiltration natural airflow, L/s

Equation A-2 Half-linear method for combining mechanical ventilation and infiltration airflows.

The results for temperature-controlled ventilation were markedly different when using quadrature as opposed to the half-linear method. The quadrature method would suggest that at cold outside temperatures (i.e., stack-dominated conditions), the natural stack airflow would dominate the small fan airflow, thus limiting the overall impact on house airflow (and HVAC load) of turning the fan on and off. For example, if the stack airflow was 60 l/s and the fan flow was 15 l/s, turning the fan off would only change house airflow (estimated by quadrature) by 1.8 l/s ((60^2+15^2)^0.5). For comparison, the half-linear method, predicts a change in house airflow of 7.5 l/s, a factor of 4 greater than the prediction made by the quadrature method. The half-linear method was developed specifically from measurements made in stack-dominated scenarios.

Accordingly, the half-linear method appeared to be more accurate in terms of estimating the changes in energy use and air exchange rate resulting from temperature control. In other words, when looking at the overall change in annual average AER predicted by the detailed REGCAP model, and comparing it with the simplified Excel predictions, quadrature generally under-predicted this change, whereas half-linear made better estimates. This conclusion was based off of a limited examination of the data, which lacked comprehensive varying of potentially important factors, such as climate zone and airtightness. Either way, this does not indicate which method is better at predicting the overall value more accurately, but it did suggest that the half-linear method was better at predicting the change in AER and building load resulting from temperature control.

B. Appendix 2 Initial Simulation Results

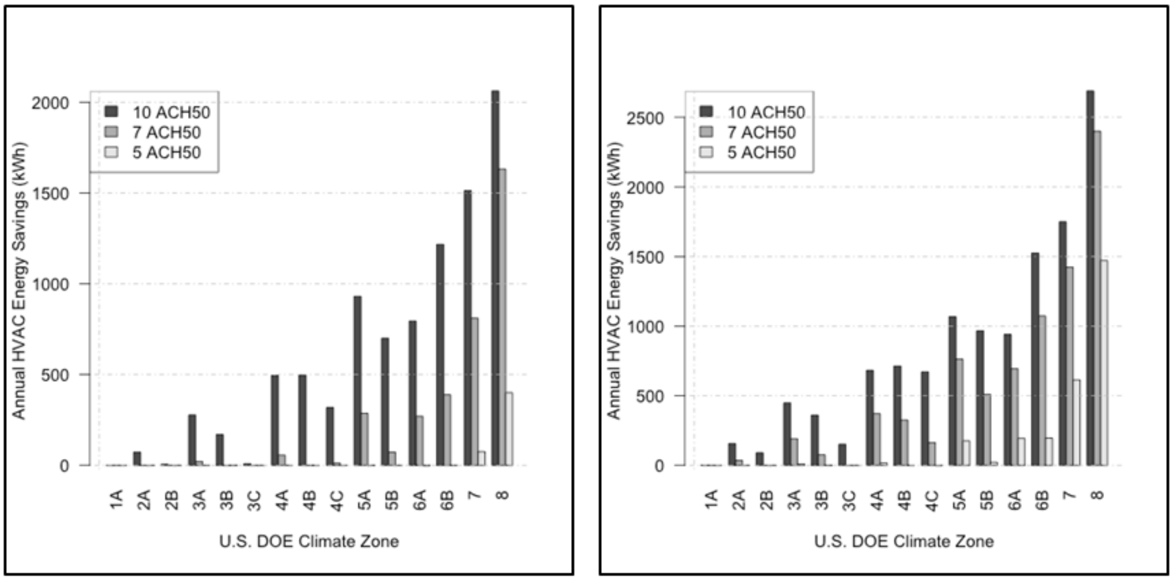

Figure B-1 Compliant sized ventilation fan, turned off at a single outdoor temperature, estimated to provide 100% of the 62.2-2013 Total Ventilation Rate. Single-story (left) and two-story (right). Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

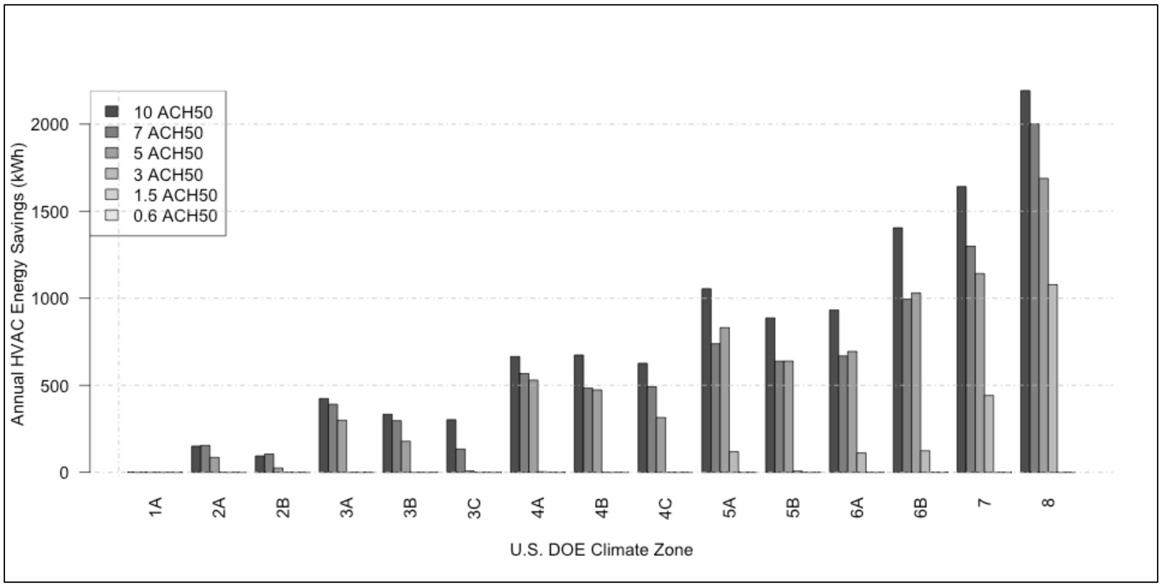

Figure B-2 Single-story home using two temperature cut-offs, designed to provide 100% and 50% of the 62.2-2013 Total Ventilation Rate by natural infiltration. Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

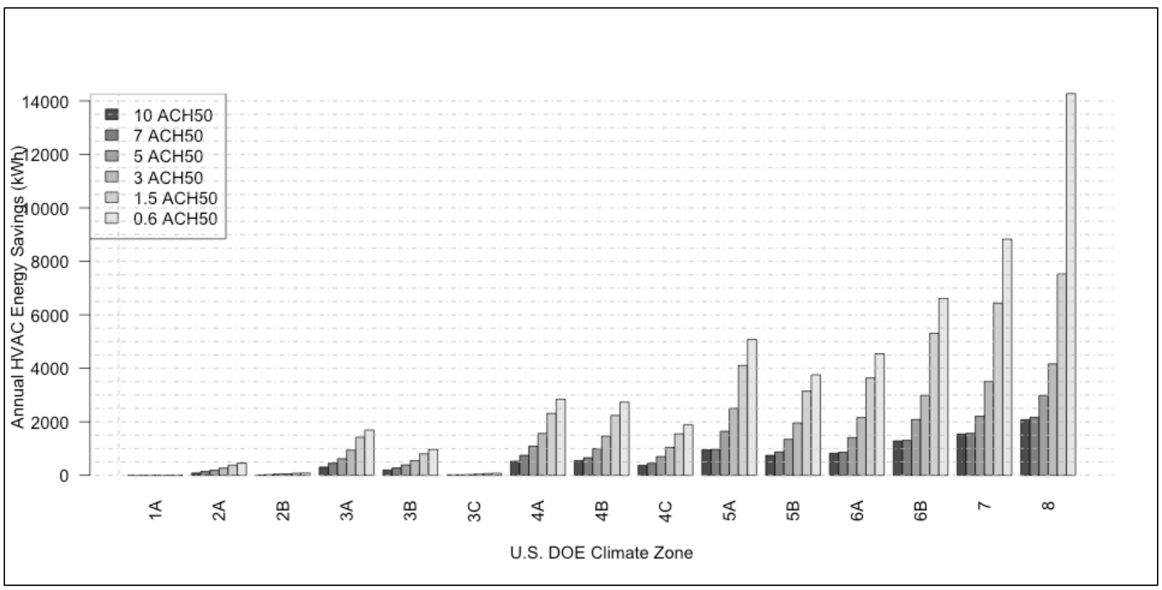

Figure B-3 Single-story home using 5C as a temperature cut-off for all climate zones and airtightness levels. Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

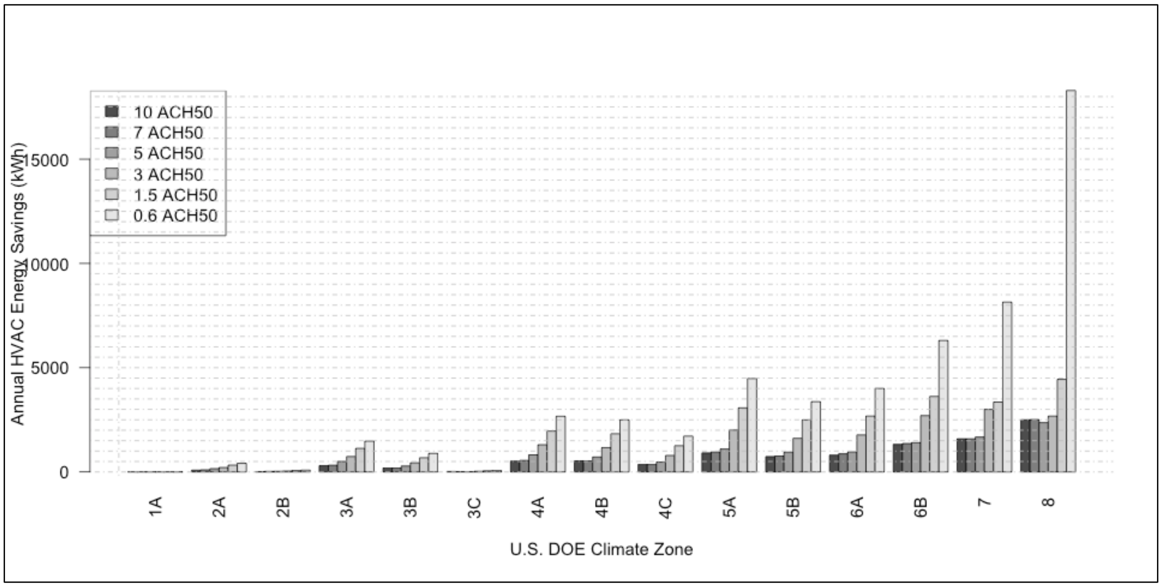

Figure B-4 Two- story home using 5C as a temperature cut-off for all climate zones and airtightness levels. Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

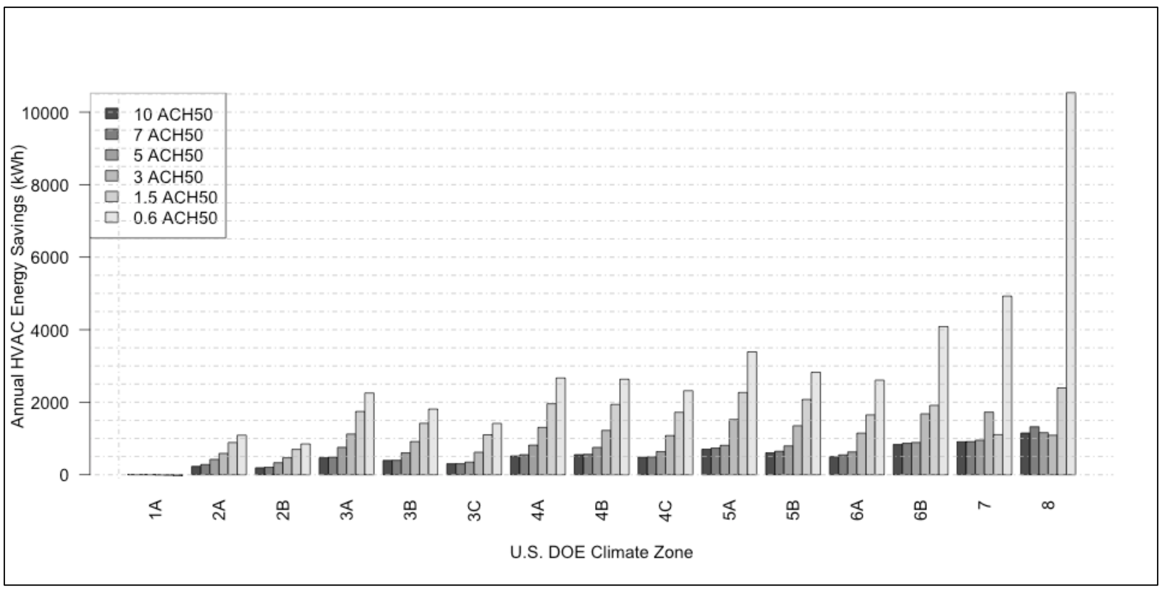

Figure B-5 Two-story home with a single cut-off temperature at the 25th percentile lowest temperature of the year, based on TMY3 climate data. Fan sized to 62.2-2013 Equation 4.1b, NOT compliant with 62.2-2013.

Airtightness (ACH_{50})	Climate Zone	1-Story Savings (kWh)				2-Story Savings (kWh)			
		Inf	Inf2	$Q25^{th}$	5°C	Inf	Inf2	$Q25^{th}$	5°C
10	1A	0	1	6	0	2	6	8	0
10	2A	73	151	235	86	157	197	230	84
10	2B	6	94	201	13	91	143	192	14
10	3A	278	424	464	307	448	512	467	298

10	3B	170	333	410	200	361	420	395	191
10	3C	9	303	316	18	152	382	301	19
10	4A	495	665	526	526	682	761	518	518
10	4B	498	674	581	552	713	776	554	530
10	4C	319	627	510	375	671	772	481	361
10	5A	931	1055	719	957	1067	1114	704	912
10	5B	700	887	635	748	966	1033	607	737
10	6A	795	932	530	827	941	1000	500	806
10	6B	1217	1405	819	1286	1524	1604	833	1323
10	7	1513	1642	904	1545	1749	1793	908	1589
10	8	2062	2193	996	2082	2688	2721	1151	2501
7	1A	0	0	5	0	0	-1	9	0
7	2A	0	154	401	147	35	152	282	100
7	2B	0	105	322	28	0	95	208	23
7	3A	22	391	700	452	191	389	482	323
7	3B	0	297	584	276	76	273	397	189
7	3C	0	134	323	17	0	259	302	13
7	4A	57	567	750	750	372	619	553	553
7	4B	0	484	699	658	326	574	562	536
7	4C	13	492	613	447	164	522	492	361
7	5A	287	739	733	971	764	988	733	953
7	5B	73	639	733	876	510	818	647	761
7	6A	271	669	559	867	694	886	547	869
7	6B	389	994	833	1305	1073	1371	866	1363
7	7	811	1299	924	1570	1423	1670	913	1586
7	8	1632	2001	1073	2171	2399	2626	1323	2512
5	1A	0	0	-2	0	0	1	5	0
5	2A	0	86	533	190	0	153	423	157
5	2B	0	25	427	46	0	78	332	29
5	3A	0	299	960	620	11	393	756	503
5	3B	0	179	825	390	0	270	601	283
5	3C	0	8	536	28	0	89	347	14
5	4A	0	530	1085	1085	17	555	817	817
5	4B	0	474	1050	995	0	488	754	715
5	4C	0	315	957	702	-1	460	640	469
5	5A	0	831	1233	1648	176	729	809	1097
5	5B	0	639	1129	1347	22	650	794	947
5	6A	-2	695	900	1409	194	664	628	958
5	6B	0	1031	1342	2086	196	919	889	1404
5	7	76	1142	1279	2214	614	1236	953	1672

5	8	401	1689	1417	2991	1471	1967	1161	2364
3	1A	0	0	-14	0	0	0	-6	0
3	2A	0	0	768	271	0	4	589	212
3	2B	0	0	631	56	0	0	467	43
3	3A	0	0	1477	939	0	79	1122	738
3	3B	0	0	1200	552	0	4	914	438
3	3C	0	0	901	43	0	0	621	29
3	4A	0	4	1567	1567	0	182	1304	1304
3	4B	0	0	1551	1467	0	80	1223	1166
3	4C	0	0	1438	1041	0	56	1080	789
3	5A	0	118	1839	2505	0	479	1524	2008
3	5B	0	7	1619	1958	0	181	1352	1611
3	6A	0	111	1364	2161	0	460	1148	1776
3	6B	0	124	1917	2990	0	640	1681	2701
3	7	0	442	2091	3507	0	1014	1725	2999
3	8	0	1078	2250	4168	0	999	1090	2677
1.5	1A	0	0	-18	0	0	0	-14	0
1.5	2A	0	0	1026	382	0	0	888	327
1.5	2B	0	0	815	77	0	0	699	71
1.5	3A	0	0	2139	1424	0	0	1745	1130
1.5	3B	0	0	1685	805	0	0	1419	678
1.5	3C	0	0	1288	67	0	0	1100	55
1.5	4A	0	0	2316	2316	0	0	1957	1957
1.5	4B	0	0	2364	2240	0	0	1939	1831
1.5	4C	0	0	2107	1551	0	0	1721	1257
1.5	5A	0	0	3114	4107	0	0	2267	3072
1.5	5B	0	0	2676	3147	0	0	2077	2496
1.5	6A	0	0	2358	3639	0	0	1651	2678
1.5	6B	0	0	3403	5312	0	0	1914	3620
1.5	7	0	0	3768	6438	0	0	1105	3349
1.5	8	0	0	2500	7532	0	0	2393	4439
0.6	1A	0	0	-33	0	0	0	-27	0
0.6	2A	0	0	1186	456	0	0	1091	412
0.6	2B	0	0	917	85	0	0	850	84
0.6	3A	0	0	2526	1694	0	0	2254	1476
0.6	3B	0	0	1977	965	0	0	1811	888
0.6	3C	0	0	1535	77	0	0	1416	65
0.6	4A	0	0	2845	2845	0	0	2668	2668
0.6	4B	0	0	2885	2737	0	0	2633	2497
0.6	4C	0	0	2552	1888	0	0	2317	1717

0.6	5A	0	0	3868	5081	0	0	3388	4477
0.6	5B	0	0	3198	3759	0	0	2824	3369
0.6	6A	0	0	2995	4547	0	0	2609	4004
0.6	6B	0	0	4374	6616	0	0	4085	6304
0.6	7	0	0	5466	8831	0	0	4926	8142
0.6	8	0	0	7290	14274	0	0	10537	18292

Table B-1 REGCAP simulation energy savings estimates for temperature controlled ventilation strategies using a fan sized to 62.2-2013 Equation 4.1b. Notably, in all cases where the fan was turned off (i.e., savings greater than 0) the relative exposure increased, which leads to non-compliance with ASHRAE 62.2-2013.

Airtightness (ACH_{50})	Climate Zone	1-Story Savings (%)				2-Story Savings (%)			
		Inf	Inf2	$Q25^{th}$	5°C	Inf	Inf2	$Q25^{th}$	5°C
10	1A	0%	0%	0%	0%	0%	0%	0%	0%
10	2A	0%	1%	2%	1%	1%	1%	2%	1%
10	2B	0%	1%	1%	0%	1%	1%	1%	0%
10	3A	1%	2%	2%	1%	2%	2%	2%	1%
10	3B	1%	2%	2%	1%	2%	2%	2%	1%
10	3C	0%	2%	2%	0%	1%	2%	2%	0%
10	4A	1%	2%	1%	1%	2%	2%	1%	1%
10	4B	2%	2%	2%	2%	2%	3%	2%	2%
10	4C	1%	2%	2%	1%	2%	3%	2%	1%
10	5A	2%	2%	2%	2%	2%	2%	2%	2%
10	5B	2%	2%	2%	2%	3%	3%	2%	2%
10	6A	2%	2%	1%	2%	2%	2%	1%	2%
10	6B	2%	3%	2%	2%	3%	3%	2%	2%
10	7	2%	2%	1%	2%	2%	2%	1%	2%
10	8	2%	2%	1%	2%	2%	2%	1%	2%
7	1A	0%	0%	0%	0%	0%	0%	0%	0%
7	2A	0%	1%	3%	1%	0%	1%	2%	1%
7	2B	0%	1%	2%	0%	0%	1%	1%	0%
7	3A	0%	1%	3%	2%	1%	2%	2%	1%
7	3B	0%	1%	3%	1%	0%	1%	2%	1%
7	3C	0%	1%	2%	0%	0%	1%	2%	0%
7	4A	0%	2%	2%	2%	1%	2%	2%	2%
7	4B	0%	2%	2%	2%	1%	2%	2%	2%
7	4C	0%	2%	2%	2%	1%	2%	2%	1%
7	5A	1%	2%	2%	2%	2%	2%	2%	2%
7	5B	0%	2%	2%	3%	2%	3%	2%	2%
7	6A	1%	2%	1%	2%	2%	2%	1%	2%

7	6B	1%	2%	2%	3%	2%	3%	2%	3%
7	7	1%	2%	1%	2%	2%	3%	1%	2%
7	8	2%	2%	1%	2%	2%	3%	1%	2%
5	1A	0%	0%	0%	0%	0%	0%	0%	0%
5	2A	0%	1%	3%	1%	0%	1%	3%	1%
5	2B	0%	0%	3%	0%	0%	0%	2%	0%
5	3A	0%	1%	4%	2%	0%	2%	3%	2%
5	3B	0%	1%	4%	2%	0%	1%	3%	1%
5	3C	0%	0%	3%	0%	0%	1%	2%	0%
5	4A	0%	2%	3%	3%	0%	2%	3%	3%
5	4B	0%	2%	4%	3%	0%	2%	3%	3%
5	4C	0%	1%	3%	3%	0%	2%	3%	2%
5	5A	0%	2%	3%	4%	0%	2%	2%	3%
5	5B	0%	2%	3%	4%	0%	2%	3%	3%
5	6A	0%	2%	2%	4%	1%	2%	2%	3%
5	6B	0%	2%	3%	4%	0%	2%	2%	3%
5	7	0%	2%	2%	3%	1%	2%	2%	3%
5	8	0%	2%	1%	3%	2%	2%	1%	2%
3	1A	0%	0%	0%	0%	0%	0%	0%	0%
3	2A	0%	0%	5%	2%	0%	0%	4%	1%
3	2B	0%	0%	4%	0%	0%	0%	3%	0%
3	3A	0%	0%	6%	4%	0%	0%	5%	3%
3	3B	0%	0%	6%	3%	0%	0%	5%	2%
3	3C	0%	0%	5%	0%	0%	0%	4%	0%
3	4A	0%	0%	5%	5%	0%	1%	4%	4%
3	4B	0%	0%	5%	5%	0%	0%	5%	4%
3	4C	0%	0%	5%	4%	0%	0%	4%	3%
3	5A	0%	0%	5%	6%	0%	1%	4%	5%
3	5B	0%	0%	5%	6%	0%	1%	4%	5%
3	6A	0%	0%	4%	6%	0%	1%	3%	5%
3	6B	0%	0%	4%	6%	0%	1%	4%	6%
3	7	0%	1%	3%	6%	0%	2%	3%	5%
3	8	0%	1%	2%	4%	0%	1%	1%	3%
1.5	1A	0%	0%	0%	0%	0%	0%	0%	0%
1.5	2A	0%	0%	7%	2%	0%	0%	6%	2%
1.5	2B	0%	0%	5%	0%	0%	0%	4%	0%
1.5	3A	0%	0%	8%	5%	0%	0%	7%	5%
1.5	3B	0%	0%	8%	4%	0%	0%	7%	3%
1.5	3C	0%	0%	7%	0%	0%	0%	6%	0%
1.5	4A	0%	0%	7%	7%	0%	0%	6%	6%

1.5	4B	0%	0%	8%	8%	0%	0%	7%	7%
1.5	4C	0%	0%	8%	6%	0%	0%	7%	5%
1.5	5A	0%	0%	8%	10%	0%	0%	6%	8%
1.5	5B	0%	0%	8%	9%	0%	0%	7%	8%
1.5	6A	0%	0%	6%	10%	0%	0%	5%	8%
1.5	6B	0%	0%	7%	11%	0%	0%	4%	8%
1.5	7	0%	0%	6%	10%	0%	0%	2%	6%
1.5	8	0%	0%	3%	8%	0%	0%	3%	5%
0.6	1A	0%	0%	0%	0%	0%	0%	0%	0%
0.6	2A	0%	0%	8%	3%	0%	0%	8%	3%
0.6	2B	0%	0%	5%	0%	0%	0%	5%	1%
0.6	3A	0%	0%	10%	6%	0%	0%	9%	6%
0.6	3B	0%	0%	9%	5%	0%	0%	9%	5%
0.6	3C	0%	0%	8%	0%	0%	0%	8%	0%
0.6	4A	0%	0%	8%	8%	0%	0%	9%	9%
0.6	4B	0%	0%	10%	9%	0%	0%	10%	9%
0.6	4C	0%	0%	9%	7%	0%	0%	9%	7%
0.6	5A	0%	0%	9%	12%	0%	0%	9%	12%
0.6	5B	0%	0%	9%	11%	0%	0%	9%	11%
0.6	6A	0%	0%	8%	12%	0%	0%	8%	12%
0.6	6B	0%	0%	9%	13%	0%	0%	9%	14%
0.6	7	0%	0%	9%	14%	0%	0%	8%	14%
0.6	8	0%	0%	7%	14%	0%	0%	11%	19%

Table B-2 REGCAP simulation percentage energy savings estimates (relative to the total HVAC energy estimate for the baseline, continuous, compliant home) for temperature controlled ventilation strategies using a fan sized to 62.2-2013 Equation 4.1b. Notably, in all cases where the fan was turned off (i.e., savings greater than 0) the relative exposure increased, which leads to non-compliance with ASHRAE 62.2-2013.

C. Appendix 3 Fan Upsizing Results

Value	Change in Fan Flow (m^3/s)	
	Median	Mean
	All	
	0.005	0.034
	Stories	
1	0.005	0.038
2	0.004	0.029
	Airtightness (ACH_{50})	
0.6	0.240	0.208
1.5	0.048	0.096
3	0.010	0.022
5	0.004	0.006
7	0.003	0.004
10	0.003	0.004
	Age	
Existing	0.006	0.044
New	0.004	0.024
	U.S. DOE Climate Zone	
1A	0.016	0.058
2A	0.002	0.015
2B	0.001	0.024
3A	0.003	0.029
3B	0.003	0.017
3C	0.002	0.014
4A	0.004	0.032
4B	0.006	0.031
4C	0.005	0.029
5A	0.004	0.041
5B	0.006	0.055
6A	0.004	0.028
6B	0.006	0.041
7	0.006	0.049
8	0.007	0.051
	Cut-Off Temperature Type	
5C	0.006	0.042
Infiltration	0.001	0.002
Infiltration2	0.003	0.003
Percentile	0.010	0.054

Table C-1 Summary by important factors of changes in fan airflow for all test cases where equivalence was achieved and where fan size increased.

ACH_{50}	Age	U.S. DOE Climate Zone	1-Story					2-Story				
			Fan Size (m^3/s)	Inf	Inf2	5°C	Q25th	Fan Size (m^3/s)	Inf	Inf2	5°C	Q25th
10	Existing	1A	0.0313	1.00	1.00	1.00	1.61	0.0223	1.00	1.01	1.00	1.60
10	Existing	2A	0.0306	1.00	1.05	1.03	1.29	0.0214	1.01	1.10	1.03	1.26
10	Existing	2B	0.0299	1.00	1.05	1.01	1.36	0.0205	1.00	1.09	1.01	1.35
10	Existing	3A	0.0279	1.00	1.10	1.08	1.19	0.0178	1.04	1.16	1.06	1.16
10	Existing	3B	0.0265	1.00	1.11	1.06	1.24	0.0159	1.03	1.17	1.06	1.21
10	Existing	3C	0.0182	1.00	1.14	1.01	1.36	0.0051	1.00	1.37	1.01	1.32
10	Existing	4A	0.0251	1.01	1.15	1.15	1.15	0.0141	1.08	1.24	1.12	1.12
10	Existing	4B	0.0224	1.00	1.18	1.19	1.21	0.0105	1.11	1.30	1.16	1.18
10	Existing	4C	0.0217	1.00	1.23	1.13	1.21	0.0096	1.05	1.39	1.10	1.17
10	Existing	5A	0.0182	1.05	1.22	1.25	1.15	0.0051	1.16	1.33	1.19	1.12
10	Existing	5B	0.0210	1.01	1.24	1.25	1.18	0.0087	1.13	1.40	1.20	1.15
10	Existing	6A	0.0176	1.06	1.27	1.28	1.13	0.0041	1.16	1.39	1.22	1.10
10	Existing	6B	0.0162	1.07	1.35	1.41	1.16	0.0023	1.23	1.55	1.32	1.13
10	Existing	7	0.0114	1.11	1.36	1.38	1.12	0.0000	0.00	0.00	0.00	0.00
10	Existing	8	0.0114	1.22	1.48	1.45	1.10	0.0000	0.00	0.00	0.00	0.00
7	Existing	1A	0.0398	1.00	1.00	1.00	1.59	0.0335	1.00	1.00	1.00	1.59
7	Existing	2A	0.0393	1.00	1.01	1.03	1.31	0.0328	1.00	1.04	1.03	1.29
7	Existing	2B	0.0388	1.00	1.00	1.01	1.38	0.0322	1.00	1.03	1.01	1.37
7	Existing	3A	0.0374	1.00	1.04	1.09	1.21	0.0303	1.00	1.09	1.08	1.20
7	Existing	3B	0.0364	1.00	1.03	1.07	1.27	0.0290	1.00	1.09	1.07	1.25
7	Existing	3C	0.0306	1.00	1.00	1.01	1.37	0.0214	1.00	1.08	1.01	1.39
7	Existing	4A	0.0354	1.00	1.07	1.19	1.19	0.0277	1.00	1.13	1.17	1.17
7	Existing	4B	0.0335	1.00	1.09	1.22	1.25	0.0252	1.00	1.16	1.21	1.23
7	Existing	4C	0.0330	1.00	1.06	1.15	1.24	0.0246	1.00	1.19	1.14	1.23
7	Existing	5A	0.0306	1.00	1.12	1.34	1.19	0.0214	1.02	1.19	1.28	1.16
7	Existing	5B	0.0325	1.00	1.11	1.30	1.22	0.0239	1.00	1.21	1.27	1.20
7	Existing	6A	0.0301	1.00	1.13	1.37	1.17	0.0208	1.03	1.23	1.32	1.15
7	Existing	6B	0.0292	1.00	1.18	1.54	1.21	0.0195	1.03	1.30	1.47	1.18
7	Existing	7	0.0258	1.01	1.19	1.56	1.16	0.0150	1.07	1.32	1.44	1.13
7	Existing	8	0.0258	1.04	1.25	1.68	1.14	0.0150	1.18	1.44	1.53	1.11
5	Existing	1A	0.0454	1.00	1.00	1.00	1.71	0.0409	1.00	1.00	1.00	1.59
5	Existing	2A	0.0451	1.00	1.00	1.04	1.43	0.0405	1.00	1.01	1.04	1.33
5	Existing	2B	0.0447	1.00	1.00	1.01	1.51	0.0400	1.00	1.00	1.01	1.40
5	Existing	3A	0.0437	1.00	1.00	1.11	1.28	0.0386	1.00	1.02	1.09	1.22
5	Existing	3B	0.0430	1.00	1.08	1.08	1.33	0.0377	1.00	1.08	1.08	1.28
5	Existing	3C	0.0389	1.00	1.00	1.01	1.38	0.0323	1.00	1.00	1.01	1.37

5	Existing	4A	0.0423	1.00	1.01	1.25	1.25	0.0368	1.00	1.05	1.20	1.20
5	Existing	4B	0.0409	1.00	1.00	1.26	1.29	0.0350	1.00	1.06	1.24	1.26
5	Existing	4C	0.0406	1.00	1.00	1.16	1.27	0.0346	1.00	1.03	1.15	1.25
5	Existing	5A	0.0389	1.00	1.03	1.44	1.24	0.0323	1.00	1.10	1.36	1.21
5	Existing	5B	0.0403	1.00	1.01	1.37	1.26	0.0341	1.00	1.08	1.32	1.23
5	Existing	6A	0.0385	1.00	1.04	1.51	1.22	0.0318	1.00	1.11	1.40	1.19
5	Existing	6B	0.0378	1.00	1.04	1.72	1.25	0.0309	1.00	1.14	1.58	1.22
5	Existing	7	0.0354	1.00	1.07	1.72	1.20	0.0277	1.00	1.17	1.60	1.18
5	Existing	8	0.0354	1.00	1.13	2.09	1.18	0.0277	1.00	1.20	1.74	1.15
3	Existing	1A	0.0511	1.00	1.00	1.00	2.56	0.0484	1.00	1.00	1.00	1.92
3	Existing	2A	0.0508	1.00	1.00	1.07	2.14	0.0481	1.00	1.00	1.05	1.65
3	Existing	2B	0.0506	1.00	1.00	1.01	2.19	0.0478	1.00	1.00	1.01	1.73
3	Existing	3A	0.0500	1.00	1.00	1.24	1.76	0.0470	1.00	1.00	1.15	1.42
3	Existing	3B	0.0496	1.00	1.00	1.13	1.72	0.0464	1.00	1.00	1.10	1.48
3	Existing	3C	0.0471	1.00	1.00	1.01	1.63	0.0432	1.00	1.00	1.01	1.49
3	Existing	4A	0.0492	1.00	1.00	1.66	1.66	0.0459	1.00	1.00	1.37	1.37
3	Existing	4B	0.0484	1.00	1.00	1.53	1.61	0.0448	1.00	1.00	1.35	1.39
3	Existing	4C	0.0482	1.00	1.00	1.32	1.66	0.0445	1.00	1.00	1.21	1.40
3	Existing	5A	0.0471	1.00	1.00	2.62	1.51	0.0432	1.00	1.00	1.67	1.31
3	Existing	5B	0.0480	1.00	1.00	2.08	1.60	0.0443	1.00	1.00	1.54	1.35
3	Existing	6A	0.0469	1.00	1.00	3.30	1.50	0.0429	1.00	1.00	1.82	1.30
3	Existing	6B	0.0465	1.00	1.00	6.53	1.53	0.0424	1.00	1.00	2.30	1.32
3	Existing	7	0.0451	1.00	1.00	7.60	1.37	0.0405	1.00	1.01	2.23	1.25
3	Existing	8	0.0451	1.00	1.00	8.88	1.34	0.0405	1.00	1.06	4.66	1.24
1.5	Existing	1A	0.0553	1.00	1.00	1.00	7.24	0.0539	1.00	1.00	1.00	5.40
1.5	Existing	2A	0.0552	1.00	1.00	1.12	7.25	0.0538	1.00	1.00	1.10	4.19
1.5	Existing	2B	0.0551	1.00	1.00	1.01	7.13	0.0537	1.00	1.00	1.01	3.71
1.5	Existing	3A	0.0548	1.00	1.00	1.73	7.12	0.0533	1.00	1.00	1.48	3.10
1.5	Existing	3B	0.0546	1.00	1.00	1.21	3.10	0.0530	1.00	1.00	1.18	2.37
1.5	Existing	3C	0.0533	1.00	1.00	1.01	2.45	0.0513	1.00	1.00	1.01	2.05
1.5	Existing	4A	0.0544	1.00	1.00	7.36	7.36	0.0527	1.00	1.00	3.04	3.04
1.5	Existing	4B	0.0539	1.00	1.00	2.37	2.82	0.0522	1.00	1.00	1.96	2.19
1.5	Existing	4C	0.0538	1.00	1.00	1.89	3.94	0.0520	1.00	1.00	1.61	2.52
1.5	Existing	5A	0.0533	1.00	1.00	7.50	6.41	0.0513	1.00	1.00	7.79	2.59
1.5	Existing	5B	0.0537	1.00	1.00	7.44	4.16	0.0519	1.00	1.00	6.32	2.52
1.5	Existing	6A	0.0532	1.00	1.00	7.52	7.52	0.0512	1.00	1.00	7.81	2.74
1.5	Existing	6B	0.0530	1.00	1.00	7.55	4.30	0.0509	1.00	1.00	7.85	2.48
1.5	Existing	7	0.0523	1.00	1.00	7.65	4.83	0.0500	1.00	1.00	8.00	2.21
1.5	Existing	8	0.0523	1.00	1.00	7.65	4.30	0.0500	1.00	1.00	8.00	2.20
0.6	Existing	1A	0.0578	1.00	1.00	1.00	6.92	0.0573	1.00	1.00	1.00	6.98
0.6	Existing	2A	0.0578	1.00	1.00	1.16	6.92	0.0572	1.00	1.00	1.15	6.99

0.6	Existing	2B	0.0577	1.00	1.00	1.02	6.93	0.0572	1.00	1.00	1.02	7.00
0.6	Existing	3A	0.0576	1.00	1.00	4.47	6.94	0.0570	1.00	1.00	2.99	7.02
0.6	Existing	3B	0.0575	1.00	1.00	1.30	6.95	0.0569	1.00	1.00	1.28	7.03
0.6	Existing	3C	0.0570	1.00	1.00	1.01	4.80	0.0562	1.00	1.00	1.01	3.89
0.6	Existing	4A	0.0575	1.00	1.00	6.96	6.96	0.0568	1.00	1.00	7.04	7.04
0.6	Existing	4B	0.0573	1.00	1.00	5.14	6.98	0.0566	1.00	1.00	3.98	6.93
0.6	Existing	4C	0.0572	1.00	1.00	4.83	6.99	0.0565	1.00	1.00	3.27	7.08
0.6	Existing	5A	0.0570	1.00	1.00	7.01	7.01	0.0562	1.00	1.00	7.11	7.11
0.6	Existing	5B	0.0572	1.00	1.00	6.99	6.99	0.0565	1.00	1.00	7.08	7.08
0.6	Existing	6A	0.0570	1.00	1.00	7.02	7.02	0.0562	1.00	1.00	7.12	7.12
0.6	Existing	6B	0.0569	1.00	1.00	7.03	7.03	0.0561	1.00	1.00	7.13	7.13
0.6	Existing	7	0.0566	1.00	1.00	7.06	7.06	0.0557	1.00	1.00	7.18	7.18
0.6	Existing	8	0.0566	1.00	1.00	7.06	7.06	0.0557	1.00	1.00	7.18	7.18
10	New	1A	0.0151	1.00	1.02	1.00	1.55	0.0144	1.00	1.04	1.00	1.56
10	New	2A	0.0144	1.02	1.11	1.03	1.25	0.0144	1.08	1.19	1.03	1.24
10	New	2B	0.0144	1.00	1.11	1.01	1.36	0.0144	1.05	1.21	1.00	1.34
10	New	3A	0.0144	1.06	1.19	1.06	1.16	0.0144	1.15	1.30	1.06	1.15
10	New	3B	0.0144	1.05	1.20	1.06	1.21	0.0144	1.16	1.35	1.06	1.20
10	New	3C	0.0144	1.00	1.45	1.01	1.35	0.0144	1.13	1.87	1.01	1.34
10	New	4A	0.0144	1.12	1.29	1.13	1.13	0.0144	1.23	1.42	1.12	1.12
10	New	4B	0.0144	1.16	1.37	1.18	1.19	0.0144	1.33	1.59	1.17	1.19
10	New	4C	0.0144	1.09	1.48	1.11	1.19	0.0144	1.39	1.96	1.11	1.18
10	New	5A	0.0144	1.22	1.43	1.24	1.14	0.0144	1.37	1.63	1.23	1.13
10	New	5B	0.0144	1.20	1.51	1.22	1.16	0.0144	1.45	1.85	1.21	1.16
10	New	6A	0.0144	1.25	1.52	1.27	1.13	0.0144	1.46	1.83	1.26	1.12
10	New	6B	0.0144	1.36	1.76	1.40	1.16	0.0144	1.68	2.21	1.38	1.15
10	New	7	0.0144	1.39	1.77	1.41	1.12	0.0144	1.65	2.25	1.39	1.12
10	New	8	0.0144	1.47	1.93	1.49	1.10	0.0144	1.76	2.47	1.46	1.10
7	New	1A	0.0235	1.00	1.00	1.00	1.56	0.0172	1.00	1.01	1.00	1.56
7	New	2A	0.0230	1.00	1.05	1.03	1.29	0.0166	1.01	1.10	1.03	1.27
7	New	2B	0.0226	1.00	1.04	1.01	1.36	0.0159	1.00	1.10	1.01	1.37
7	New	3A	0.0211	1.00	1.09	1.08	1.19	0.0144	1.03	1.17	1.07	1.17
7	New	3B	0.0202	1.00	1.10	1.07	1.25	0.0144	1.02	1.18	1.06	1.23
7	New	3C	0.0144	1.00	1.11	1.01	1.37	0.0144	1.00	1.39	1.01	1.37
7	New	4A	0.0192	1.01	1.14	1.16	1.16	0.0144	1.07	1.25	1.14	1.14
7	New	4B	0.0173	1.00	1.17	1.20	1.22	0.0144	1.09	1.31	1.19	1.21
7	New	4C	0.0168	1.00	1.21	1.13	1.22	0.0144	1.04	1.40	1.12	1.20
7	New	5A	0.0144	1.04	1.21	1.27	1.15	0.0144	1.16	1.38	1.25	1.15
7	New	5B	0.0163	1.01	1.22	1.26	1.19	0.0144	1.12	1.43	1.24	1.18
7	New	6A	0.0144	1.05	1.25	1.30	1.14	0.0144	1.19	1.46	1.29	1.14
7	New	6B	0.0144	1.05	1.33	1.45	1.18	0.0144	1.26	1.64	1.43	1.17

7	New	7	0.0144	1.11	1.37	1.46	1.14	0.0144	1.31	1.68	1.43	1.13
7	New	8	0.0144	1.23	1.51	1.56	1.12	0.0144	1.40	1.85	1.53	1.11
5	New	1A	0.0292	1.00	1.00	1.00	1.54	0.0247	1.00	1.00	1.00	1.54
5	New	2A	0.0288	1.00	1.01	1.03	1.30	0.0242	1.00	1.04	1.03	1.29
5	New	2B	0.0285	1.00	1.00	1.01	1.37	0.0238	1.00	1.03	1.01	1.37
5	New	3A	0.0274	1.00	1.03	1.09	1.21	0.0224	1.00	1.08	1.08	1.20
5	New	3B	0.0268	1.00	1.03	1.07	1.26	0.0215	1.00	1.13	1.07	1.26
5	New	3C	0.0226	1.00	1.00	1.01	1.36	0.0160	1.00	1.06	1.01	1.39
5	New	4A	0.0261	1.00	1.07	1.19	1.19	0.0206	1.00	1.12	1.17	1.17
5	New	4B	0.0247	1.00	1.08	1.23	1.25	0.0188	1.00	1.16	1.22	1.24
5	New	4C	0.0243	1.00	1.05	1.15	1.24	0.0183	1.00	1.18	1.14	1.23
5	New	5A	0.0226	1.00	1.12	1.34	1.19	0.0160	1.02	1.19	1.29	1.17
5	New	5B	0.0240	1.00	1.10	1.30	1.22	0.0179	1.00	1.20	1.28	1.20
5	New	6A	0.0223	1.00	1.13	1.38	1.18	0.0156	1.03	1.22	1.33	1.15
5	New	6B	0.0216	1.00	1.17	1.54	1.21	0.0147	1.03	1.29	1.48	1.19
5	New	7	0.0192	1.00	1.18	1.56	1.17	0.0144	1.07	1.32	1.49	1.14
5	New	8	0.0192	1.03	1.23	1.69	1.14	0.0144	1.19	1.45	1.60	1.13
3	New	1A	0.0348	1.00	1.00	1.00	1.75	0.0321	1.00	1.00	1.00	1.58
3	New	2A	0.0346	1.00	1.00	1.04	1.53	0.0318	1.00	1.00	1.04	1.37
3	New	2B	0.0344	1.00	1.00	1.01	1.59	0.0316	1.00	1.00	1.01	1.43
3	New	3A	0.0338	1.00	1.00	1.14	1.36	0.0307	1.00	1.00	1.10	1.25
3	New	3B	0.0334	1.00	1.08	1.08	1.40	0.0302	1.00	1.08	1.08	1.29
3	New	3C	0.0309	1.00	1.00	1.01	1.42	0.0269	1.00	1.00	1.01	1.35
3	New	4A	0.0329	1.00	1.00	1.31	1.31	0.0297	1.00	1.01	1.23	1.23
3	New	4B	0.0321	1.00	1.00	1.29	1.33	0.0286	1.00	1.01	1.25	1.27
3	New	4C	0.0319	1.00	1.00	1.18	1.34	0.0283	1.00	1.00	1.15	1.25
3	New	5A	0.0309	1.00	1.01	1.58	1.28	0.0269	1.00	1.04	1.41	1.22
3	New	5B	0.0317	1.00	1.00	1.46	1.30	0.0280	1.00	1.02	1.34	1.25
3	New	6A	0.0307	1.00	1.01	1.69	1.27	0.0267	1.00	1.05	1.46	1.21
3	New	6B	0.0303	1.00	1.01	2.02	1.28	0.0261	1.00	1.06	1.65	1.25
3	New	7	0.0288	1.00	1.03	2.02	1.23	0.0242	1.00	1.09	1.66	1.19
3	New	8	0.0288	1.00	1.08	3.23	1.22	0.0242	1.00	1.15	1.93	1.17
1.5	New	1A	0.0390	1.00	1.00	1.00	3.34	0.0377	1.00	1.00	1.00	2.35
1.5	New	2A	0.0389	1.00	1.00	1.08	2.93	0.0375	1.00	1.00	1.07	2.12
1.5	New	2B	0.0388	1.00	1.00	1.01	2.66	0.0374	1.00	1.00	1.01	2.11
1.5	New	3A	0.0385	1.00	1.00	1.40	2.47	0.0370	1.00	1.00	1.27	1.82
1.5	New	3B	0.0383	1.00	1.00	1.15	1.99	0.0367	1.00	1.00	1.13	1.71
1.5	New	3C	0.0371	1.00	1.00	1.01	1.79	0.0351	1.00	1.00	1.01	1.61
1.5	New	4A	0.0381	1.00	1.00	2.46	2.46	0.0365	1.00	1.00	1.76	1.76
1.5	New	4B	0.0377	1.00	1.00	1.73	1.88	0.0359	1.00	1.00	1.54	1.62
1.5	New	4C	0.0376	1.00	1.00	1.50	2.11	0.0358	1.00	1.00	1.35	1.70

1.5	New	5A	0.0371	1.00	1.00	10.79	2.22	0.0351	1.00	1.00	3.30	1.61
1.5	New	5B	0.0375	1.00	1.00	3.77	2.12	0.0356	1.00	1.00	2.24	1.67
1.5	New	6A	0.0370	1.00	1.00	10.82	2.31	0.0350	1.00	1.00	4.56	1.61
1.5	New	6B	0.0368	1.00	1.00	10.88	2.09	0.0347	1.00	1.00	11.53	1.62
1.5	New	7	0.0360	1.00	1.00	11.10	1.96	0.0337	1.00	1.00	11.86	1.46
1.5	New	8	0.0360	1.00	1.00	11.10	1.92	0.0337	1.00	1.00	11.86	1.44
0.6	New	1A	0.0416	1.00	1.00	1.00	9.62	0.0410	1.00	1.00	1.00	9.75
0.6	New	2A	0.0415	1.00	1.00	1.12	9.63	0.0410	1.00	1.00	1.11	9.76
0.6	New	2B	0.0415	1.00	1.00	1.01	9.64	0.0409	1.00	1.00	1.01	6.62
0.6	New	3A	0.0414	1.00	1.00	2.29	9.67	0.0408	1.00	1.00	1.92	9.81
0.6	New	3B	0.0413	1.00	1.00	1.22	3.60	0.0407	1.00	1.00	1.21	2.99
0.6	New	3C	0.0408	1.00	1.00	1.01	2.68	0.0400	1.00	1.00	1.01	2.39
0.6	New	4A	0.0412	1.00	1.00	9.71	9.71	0.0405	1.00	1.00	9.87	9.87
0.6	New	4B	0.0410	1.00	1.00	2.65	3.34	0.0403	1.00	1.00	2.35	2.80
0.6	New	4C	0.0410	1.00	1.00	2.47	9.76	0.0403	1.00	1.00	2.07	5.06
0.6	New	5A	0.0408	1.00	1.00	9.81	9.81	0.0400	1.00	1.00	10.00	10.00
0.6	New	5B	0.0410	1.00	1.00	9.77	9.77	0.0402	1.00	1.00	9.95	7.02
0.6	New	6A	0.0407	1.00	1.00	9.82	9.82	0.0399	1.00	1.00	10.01	10.01
0.6	New	6B	0.0407	1.00	1.00	9.84	9.84	0.0398	1.00	1.00	10.04	8.27
0.6	New	7	0.0404	1.00	1.00	9.91	9.91	0.0395	1.00	1.00	10.14	10.14
0.6	New	8	0.0404	1.00	1.00	9.91	9.91	0.0395	1.00	1.00	10.14	10.14

Table C-2 62.2-2013 fan airflows and calculated fan upsizing factors for each test case.

D. Appendix 4 Final Simulation Results

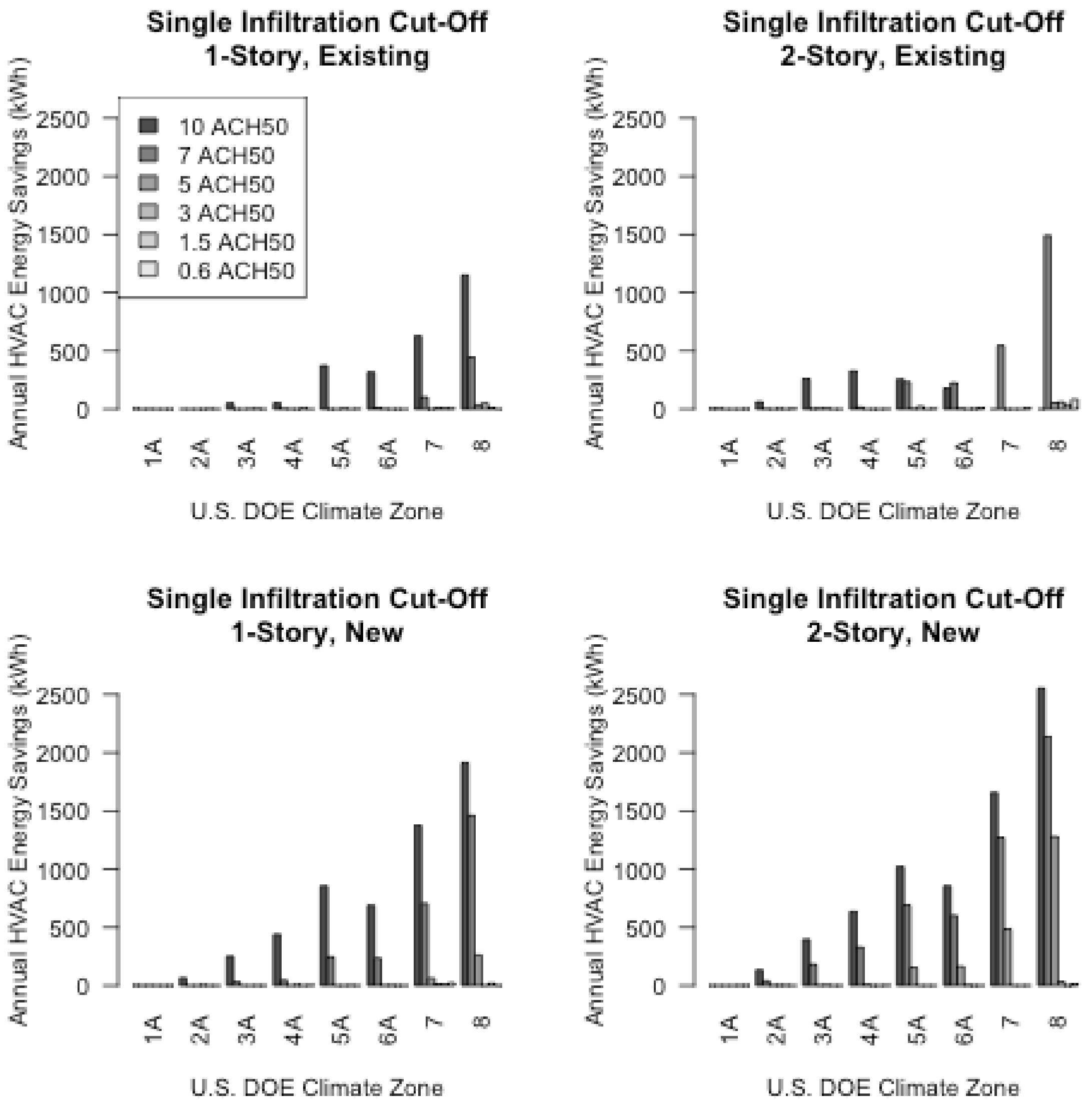

Figure D-1 Summaries of total HVAC energy savings resulting from temperature controlled ventilation, using a single infiltration based cut-off.

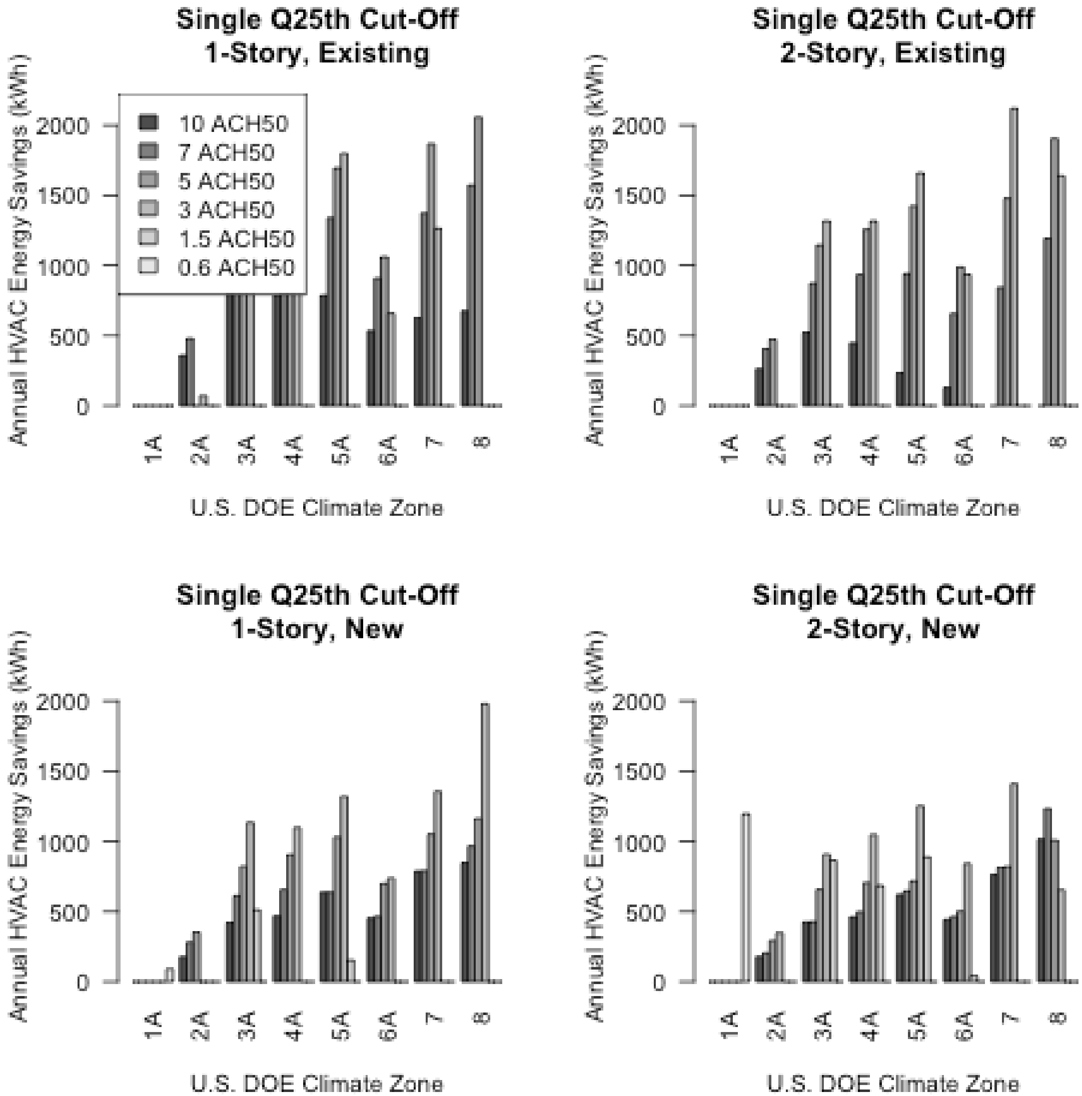

Figure D-2 Summaries of total HVAC energy savings resulting from temperature controlled ventilation, using a single cut-off temperature, calculated as the 25th percentile annual outdoor temperature for each climate zone.

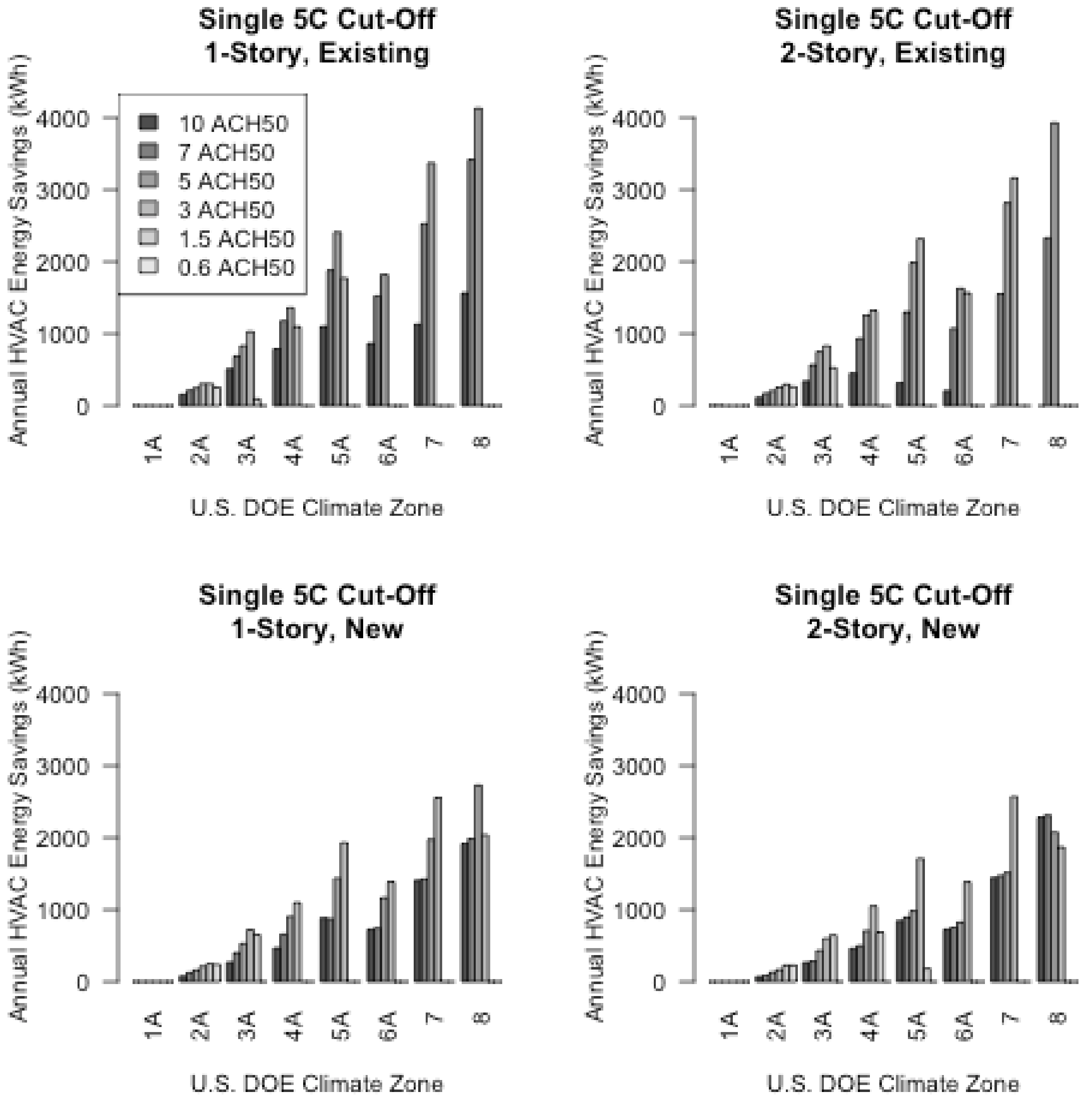

Figure D-3 Summaries of total HVAC energy savings resulting from temperature controlled ventilation, using a single temperature cut-off of 5°C.

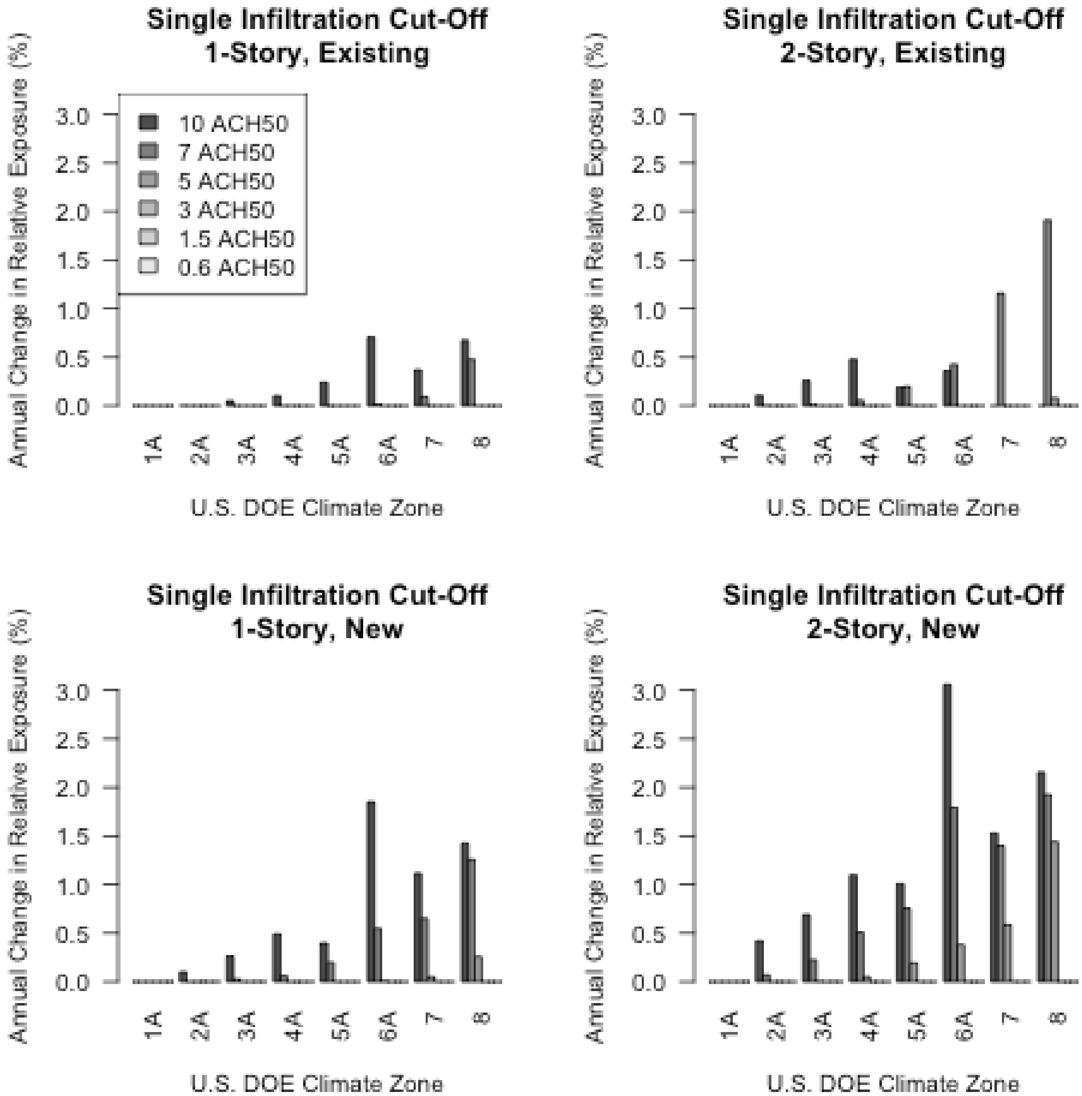

Figure D-4 Summaries of change in annual relative exposure resulting from temperature controlled ventilation, using a single infiltration based temperature cut-off.

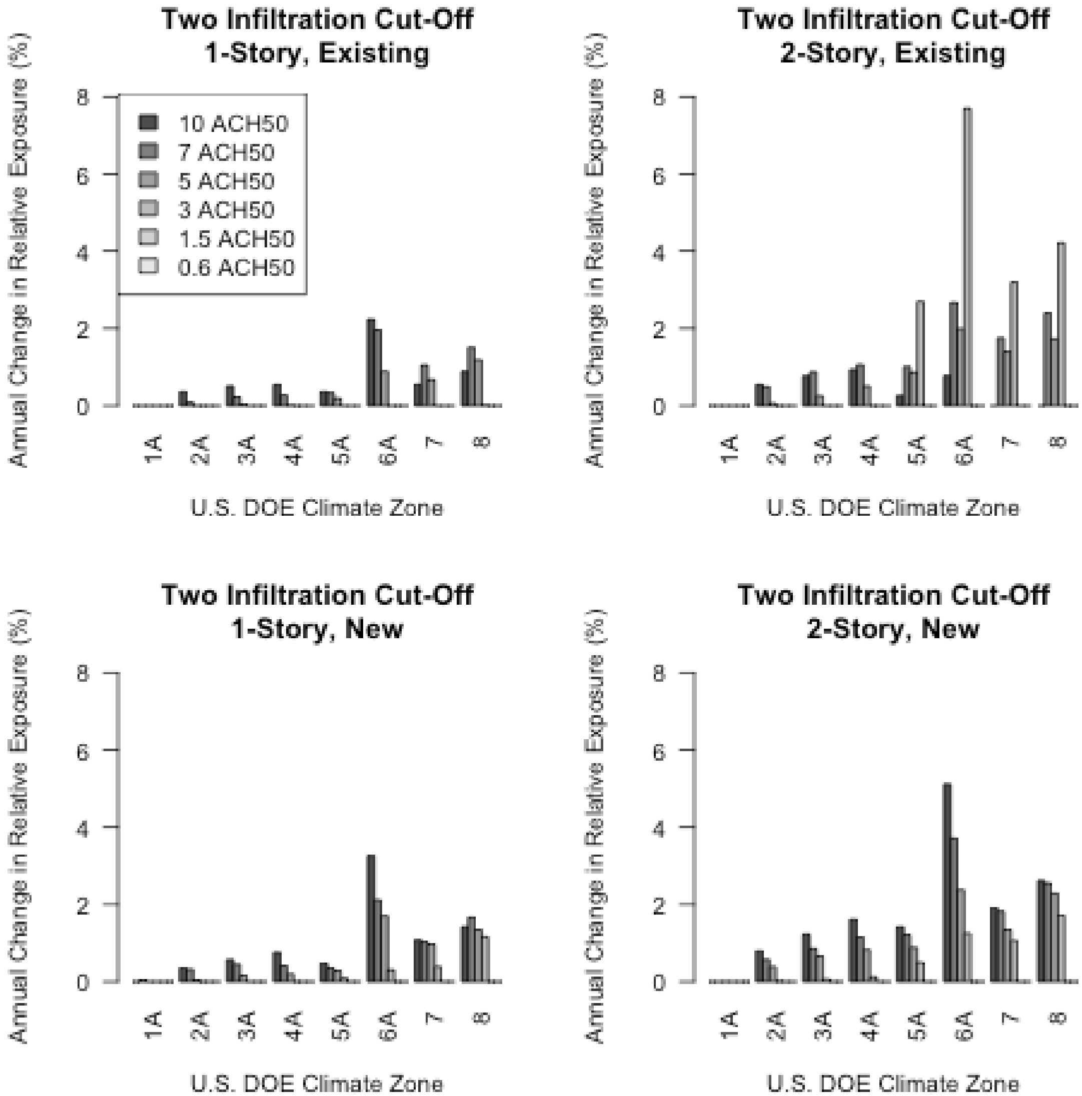

Figure D-5 Summaries of change in annual average relative exposure resulting from temperature controlled ventilation, using two infiltration based temperature cut-offs.

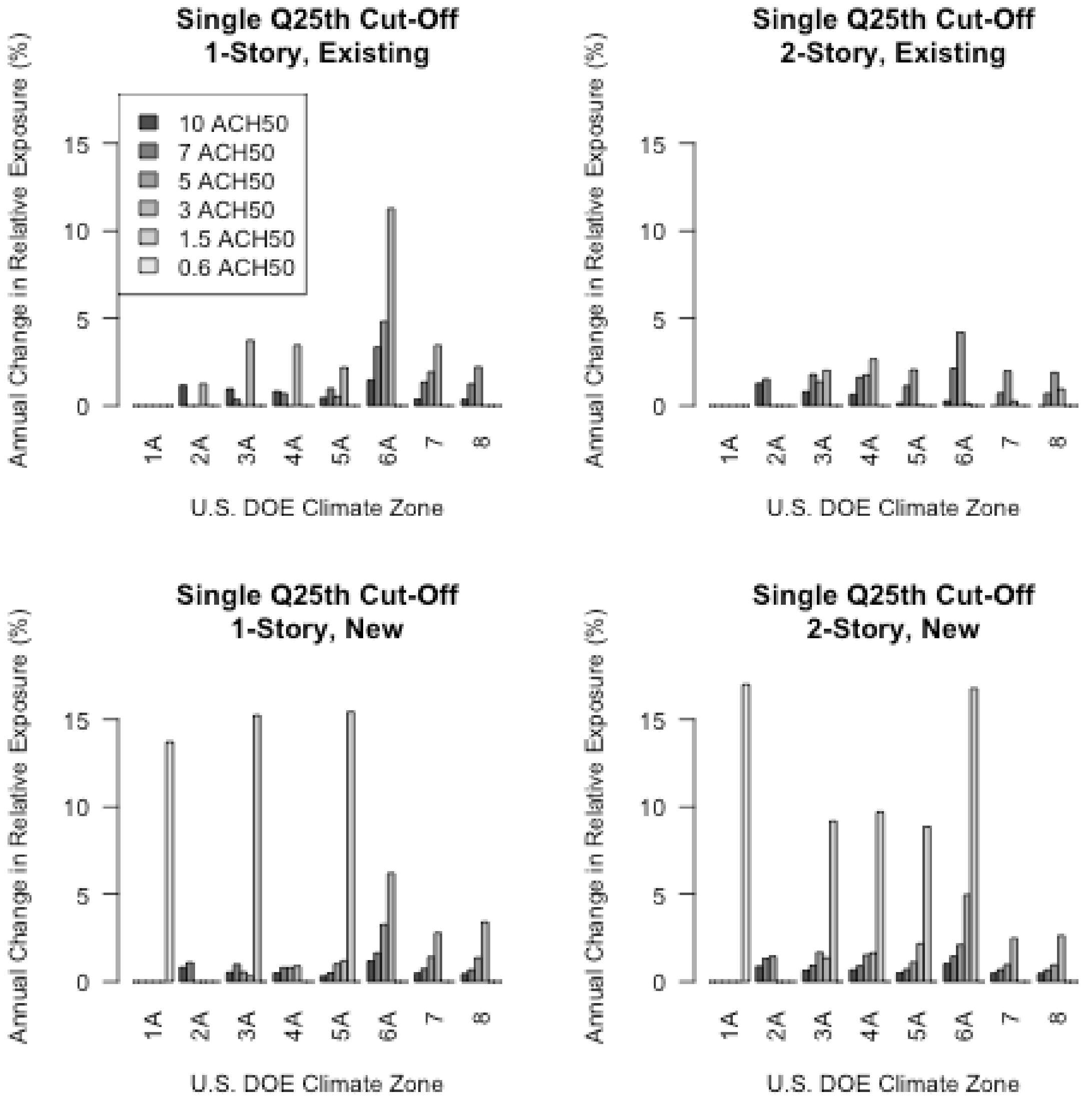

Figure D-6 Summaries of change in annual average relative exposure resulting from temperature controlled ventilation, using a single temperature cut-off, calculated as the 25th percentile of annual outdoor temperatures.

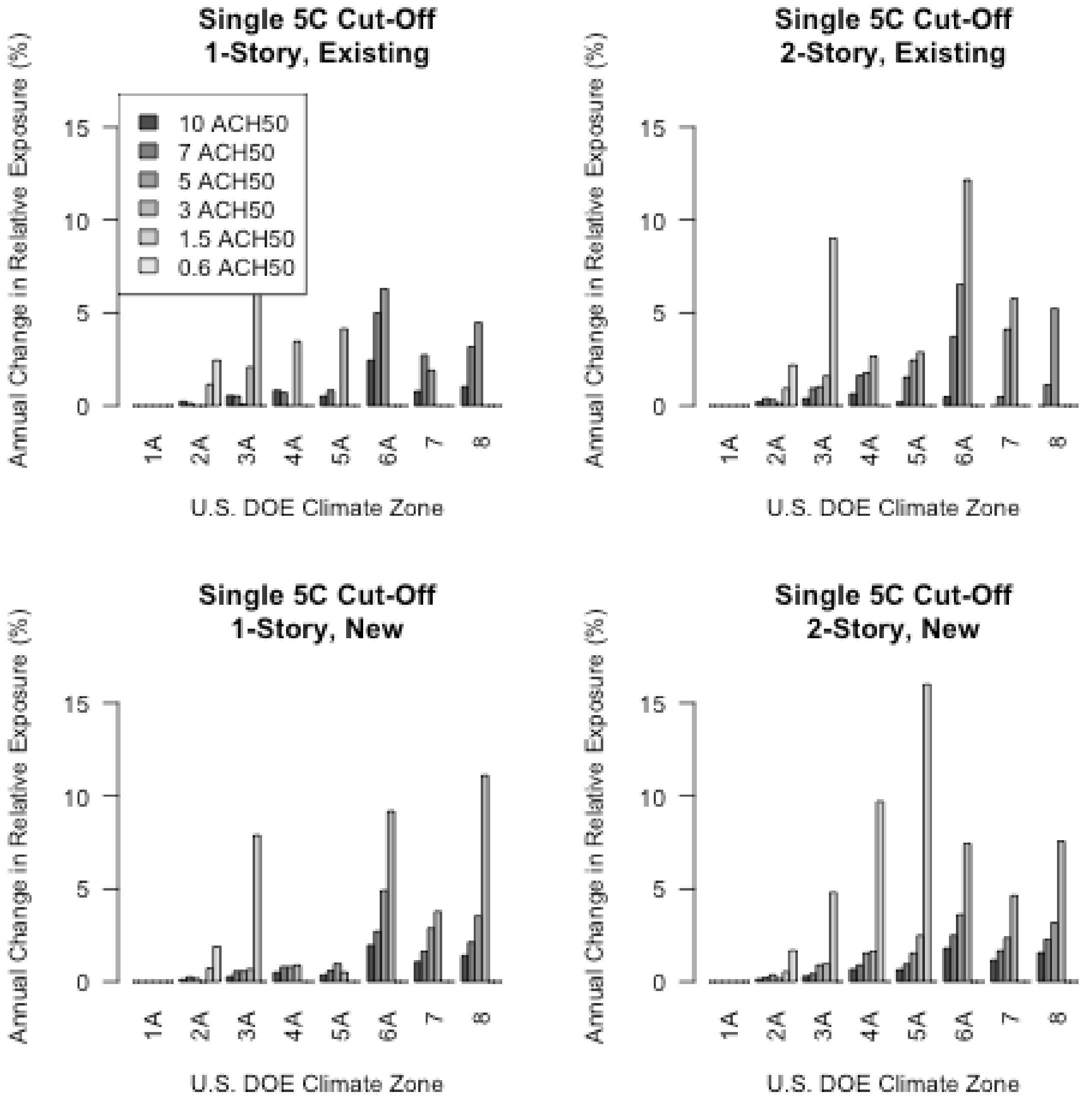

Figure D-7 Summaries of change in annual average relative exposure resulting from temperature controlled ventilation, using a single temperature cut-off of 5°C.

ACH_{50}	Age	U.S. DOE CZ	1-Story Energy Reductions (kWh)					2-Story Energy Reductions (kWh)				
			Inf	Inf2	5°C	Q25th	***Best***	Inf	Inf2	5°C	Q25th	***Best***
10	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
10	Existing	2a	0	157	157	359	***Q25th***	61	153	112	263	***Q25th***
10	Existing	3a	0	429	512	798	***Q25th***	261	422	341	523	***Q25th***
10	Existing	4a	51	567	785	785	***5C***	327	504	448	448	***Inf2***
10	Existing	5a	372	797	1099	787	***5C***	255	306	316	232	***5C***
10	Existing	6a	318	626	866	534	***5C***	176	223	207	128	***Inf2***
10	Existing	7a	628	906	1125	627	***5C***	0	0	0	0	***None***
10	Existing	8	1150	1427	1565	673	***5C***	0	0	0	0	***None***
7	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
7	Existing	2a	0	104	211	479	***Q25th***	0	157	172	404	***Q25th***
7	Existing	3a	0	344	690	1084	***Q25th***	0	414	567	873	***Q25th***
7	Existing	4a	0	560	1178	1178	***5C***	0	591	932	932	***5C***
7	Existing	5a	0	872	1881	1339	***5C***	233	787	1299	940	***5C***
7	Existing	6a	0	700	1523	908	***5C***	225	657	1073	655	***5C***
7	Existing	7a	103	1143	2527	1373	***5C***	545	1045	1555	841	***5C***
7	Existing	8	444	1604	3417	1572	***5C***	1490	1973	2326	1190	***5C***
5	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
5	Existing	2a	0	0	245	0	***5C***	0	62	207	473	***Q25th***
5	Existing	3a	0	0	833	1349	***Q25th***	0	296	748	1145	***Q25th***
5	Existing	4a	0	92	1359	1359	***5C***	0	481	1255	1255	***5C***
5	Existing	5a	0	429	2409	1693	***5C***	0	835	1983	1423	***5C***
5	Existing	6a	0	366	1816	1061	***5C***	0	688	1624	987	***5C***
5	Existing	7a	0	961	3372	1866	***5C***	0	1101	2813	1478	***5C***
5	Existing	8	0	1628	4128	2057	***5C***	0	1607	3926	1905	***5C***
3	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
3	Existing	2a	0	0	306	71	***5C***	0	0	254	0	***5C***
3	Existing	3a	0	0	1029	1424	***Q25th***	0	0	831	1316	***Q25th***
3	Existing	4a	0	0	1095	1095	***5C***	0	0	1317	1317	***5C***
3	Existing	5a	0	0	1770	1798	***Q25th***	0	0	2314	1660	***5C***
3	Existing	6a	0	0	0	657	***Q25th***	0	0	1567	935	***5C***
3	Existing	7a	0	0	0	1262	***Q25th***	0	296	3159	2119	***5C***
3	Existing	8	0	0	0	0	***None***	0	856	0	1638	***Q25th***
1.5	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
1.5	Existing	2a	0	0	305	0	***5C***	0	0	294	0	***5C***
1.5	Existing	3a	0	0	90	0	***5C***	0	0	526	0	***5C***
1.5	Existing	4a	0	0	0	0	***None***	0	0	0	0	***None***
1.5	Existing	5a	0	0	0	0	***None***	0	0	0	0	***None***
1.5	Existing	6a	0	0	0	0	***None***	0	0	0	0	***None***
1.5	Existing	7a	0	0	0	0	***None***	0	0	0	0	***None***

1.5	Existing	8	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	1	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	2a	0	0	250	0	***5C***	0	0	258	0	***5C***
0.6	Existing	3a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	4a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	5a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	6a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	7a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	Existing	8	0	0	0	0	***None***	0	0	0	0	***None***
10	New	1	0	0	0	0	***None***	0	0	0	0	***None***
10	New	2a	66	116	77	176	***Q25th***	132	146	69	177	***Q25th***
10	New	3a	252	358	270	422	***Q25th***	396	436	269	424	***Inf2***
10	New	4a	438	582	468	468	***Inf2***	634	699	461	461	***Inf2***
10	New	5a	853	981	881	638	***Inf2***	1021	1055	843	619	***Inf2***
10	New	6a	689	807	723	451	***Inf2***	853	875	724	442	***Inf2***
10	New	7a	1374	1520	1408	788	***Inf2***	1657	1697	1444	762	***Inf2***
10	New	8	1912	2039	1920	848	***Inf2***	2555	2646	2287	1016	***Inf2***
7	New	1	0	0	0	0	***None***	0	0	0	0	***None***
7	New	2a	0	122	124	279	***Q25th***	38	112	88	203	***Q25th***
7	New	3a	0	319	400	611	***Q25th***	183	326	283	427	***Q25th***
7	New	4a	47	463	656	656	***5C***	327	528	499	499	***Inf2***
7	New	5a	245	605	869	638	***5C***	691	879	890	647	***5C***
7	New	6a	234	531	746	466	***5C***	602	749	753	464	***5C***
7	New	7a	705	1081	1424	790	***5C***	1271	1471	1472	815	***5C***
7	New	8	1459	1759	1987	965	***5C***	2138	2333	2311	1233	***Inf2***
5	New	1	0	0	0	0	***None***	0	0	0	0	***None***
5	New	2a	0	70	159	353	***Q25th***	0	119	131	293	***Q25th***
5	New	3a	0	247	526	822	***Q25th***	0	309	433	658	***Q25th***
5	New	4a	0	429	905	905	***5C***	0	450	704	704	***5C***
5	New	5a	0	658	1437	1030	***5C***	155	583	982	717	***5C***
5	New	6a	0	526	1165	698	***5C***	164	505	822	502	***5C***
5	New	7a	0	873	1977	1050	***5C***	485	976	1512	820	***5C***
5	New	8	262	1281	2723	1164	***5C***	1279	1580	2077	1008	***5C***
3	New	1	0	0	0	0	***None***	0	0	0	0	***None***
3	New	2a	0	0	210	0	***5C***	0	0	165	347	***Q25th***
3	New	3a	0	0	718	1134	***Q25th***	0	0	599	908	***Q25th***
3	New	4a	0	0	1099	1099	***5C***	0	156	1046	1046	***5C***
3	New	5a	0	81	1931	1320	***5C***	0	379	1708	1253	***5C***
3	New	6a	0	79	1384	738	***5C***	0	353	1382	842	***5C***
3	New	7a	0	344	2551	1356	***5C***	0	781	2570	1408	***5C***
3	New	8	0	883	2035	1980	***Q25th***	0	695	1867	655	***5C***

1.5	New	1	0	0	0	0	***None***	0	0	0	0	***None***
1.5	New	2a	0	0	248	0	***5C***	0	0	224	0	***5C***
1.5	New	3a	0	0	650	512	***5C***	0	0	646	864	***Q25th***
1.5	New	4a	0	0	0	0	***None***	0	0	685	685	***5C***
1.5	New	5a	0	0	0	153	***Q25th***	0	0	180	887	***Q25th***
1.5	New	6a	0	0	0	0	***None***	0	0	0	41	***Q25th***
1.5	New	7a	0	0	0	0	***None***	0	0	0	0	***None***
1.5	New	8	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	1	0	0	0	90	***None***	0	0	0	1196	***None***
0.6	New	2a	0	0	238	0	***5C***	0	0	224	0	***5C***
0.6	New	3a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	4a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	5a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	6a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	7a	0	0	0	0	***None***	0	0	0	0	***None***
0.6	New	8	0	0	0	0	***None***	0	0	0	0	***None***
Note, in climate zone 4A, cut-off temperatures were identical between the 5°C and Q25th strategies. The best strategy is indicated as 5°C in these cases, but this is exactly equivalent to the Q25th strategy.												

Table D-1 Annual HVAC energy reduction estimates for all cases, upsized fans.

ACH_{50}	Stories	Age	Climate Zone	Recom-mended Cut-Off Type	62.2-2013, Fan Size (m^3/s)	FSM	Energy Savings (kWh (%))	Change in Relative Exposure (%)	Change in AER (hr-1)	Cut-Off Temperature (°C)
10	1	existing	1A	None	0.0313	None	0 (0%)	0.0	0.000	None
10	1	existing	2A	Q25th	0.0306	1.29	359 (2.2%)	1.2	-0.007	15
10	1	existing	3A	Q25th	0.0279	1.19	798 (2.8%)	1.0	0.005	9.4
10	1	existing	4A	5C	0.0251	1.15	785 (2.2%)	0.8	0.009	5
10	1	existing	5A	5C	0.0182	1.25	1099 (2.4%)	0.5	0.012	5
10	1	existing	6A	5C	0.0176	1.28	866 (2.1%)	2.4	0.005	5
10	1	existing	7	5C	0.0114	1.38	1125 (1.6%)	0.8	0.013	5
10	1	existing	8	5C	0.0114	1.45	1565 (1.4%)	1.0	0.018	5
7	1	existing	1A	None	0.0398	None	0 (0%)	0.0	0.000	None
7	1	existing	2A	Q25th	0.0393	1.31	479 (3%)	-1.2	-0.019	15
7	1	existing	3A	Q25th	0.0374	1.21	1084 (3.9%)	0.3	-0.002	9.4
7	1	existing	4A	5C	0.0354	1.19	1178 (3.4%)	0.7	0.004	5
7	1	existing	5A	5C	0.0306	1.34	1881 (4.3%)	0.8	0.008	5
7	1	existing	6A	5C	0.0301	1.37	1523 (3.8%)	5.0	-0.007	5
7	1	existing	7	5C	0.0258	1.56	2527 (3.8%)	2.7	0.013	5
7	1	existing	8	5C	0.0258	1.68	3417 (3.2%)	3.2	0.023	5
5	1	existing	1A	None	0.0454	None	0 (0%)	0.0	0.000	None
5	1	existing	2A	5C	0.0451	1.04	245 (1.5%)	-0.3	-0.002	5
5	1	existing	3A	Q25th	0.0437	1.28	1349 (4.9%)	-1.2	-0.018	9.4

5	1	existing	4A	5C	0.0423	1.25	1359 (3.9%)	-0.2	-0.011	5
5	1	existing	5A	5C	0.0389	1.44	2409 (5.6%)	-0.8	-0.012	5
5	1	existing	6A	5C	0.0385	1.51	1816 (4.6%)	6.3	-0.041	5
5	1	existing	7	5C	0.0354	1.72	3372 (5.1%)	1.9	-0.013	5
5	1	existing	8	5C	0.0354	2.09	4128 (4%)	4.5	-0.022	5
3	1	existing	1A	None	0.0511	None	0 (0%)	0.0	0.000	None
3	1	existing	2A	5C	0.0508	1.07	306 (1.9%)	-0.1	-0.010	5
3	1	existing	3A	Q25th	0.05	1.76	1424 (5.2%)	3.7	-0.144	9.4
3	1	existing	4A	5C	0.0492	1.66	1095 (3.1%)	3.5	-0.118	5
3	1	existing	5A	Q25th	0.0471	1.51	1798 (4.1%)	2.2	-0.071	1.1
3	1	existing	6A	Q25th	0.0469	1.5	657 (1.7%)	11.3	-0.098	-0.6
3	1	existing	7	Q25th	0.0451	1.37	1262 (1.9%)	3.5	-0.040	-5
3	1	existing	8	None	0.0451	None	0 (0.1%)	0.0	0.000	None
1.5	1	existing	1A	None	0.0553	None	0 (0%)	0.0	0.000	None
1.5	1	existing	2A	5C	0.0552	1.12	305 (1.9%)	1.1	-0.028	5
1.5	1	existing	3A	5C	0.0548	1.73	90 (0.3%)	13.4	-0.211	5
1.5	1	existing	4A	None	0.0544	None	0 (0%)	0.0	0.000	None
1.5	1	existing	5A	None	0.0533	None	0 (0%)	0.0	0.000	None
1.5	1	existing	6A	None	0.0532	None	0 (0%)	0.0	0.000	None
1.5	1	existing	7	None	0.0523	None	0 (0%)	0.0	0.000	None
1.5	1	existing	8	None	0.0523	None	0 (0%)	0.0	0.000	None
0.6	1	existing	1A	None	0.0578	None	0 (0%)	0.0	0.000	None
0.6	1	existing	2A	5C	0.0578	1.16	250 (1.5%)	2.4	-0.047	5
0.6	1	existing	3A	None	0.0576	None	0 (0%)	0.0	0.000	None
0.6	1	existing	4A	None	0.0575	None	0 (0%)	0.0	0.000	None
0.6	1	existing	5A	None	0.057	None	0 (0%)	0.0	0.000	None
0.6	1	existing	6A	None	0.057	None	0 (0%)	0.0	0.000	None
0.6	1	existing	7	None	0.0566	None	0 (0%)	0.0	0.000	None
0.6	1	existing	8	None	0.0566	None	0 (0%)	0.0	0.000	None
10	2	existing	1A	None	0.0223	None	0 (0%)	0.0	0.000	None
10	2	existing	2A	Q25th	0.0214	1.26	263 (1.7%)	1.3	0.000	15
10	2	existing	3A	Q25th	0.0178	1.16	523 (1.9%)	0.8	0.007	9.4
10	2	existing	4A	Inf2	0.0141	1.24	504 (1.5%)	0.9	0.009	2.6 / 13.8
10	2	existing	5A	5C	0.0051	1.19	316 (0.7%)	0.2	0.005	5
10	2	existing	6A	Inf2	0.0041	1.39	223 (0.6%)	0.8	0.002	2.6 / 13.8
10	2	existing	7	None	0	None	0 (0%)	0.0	0.000	None
10	2	existing	8	None	0	None	0 (0%)	0.0	0.000	None
7	2	existing	1A	None	0.0335	None	0 (0%)	0.0	0.000	None
7	2	existing	2A	Q25th	0.0328	1.29	404 (2.7%)	1.5	-0.009	15
7	2	existing	3A	Q25th	0.0303	1.2	873 (3.3%)	1.8	0.004	9.4
7	2	existing	4A	5C	0.0277	1.17	932 (2.8%)	1.6	0.009	5

7	2	existing	5A	5C	0.0214	1.28	1299 (3.1%)	1.5	0.012	5
7	2	existing	6A	5C	0.0208	1.32	1073 (2.8%)	3.7	0.004	5
7	2	existing	7	5C	0.015	1.44	1555 (2.4%)	0.5	0.016	5
7	2	existing	8	5C	0.015	1.53	2326 (2.3%)	1.1	0.022	5
5	2	existing	1A	None	0.0409	None	0 (0%)	0.0	0.000	None
5	2	existing	2A	Q25th	0.0405	1.33	473 (3.2%)	-0.6	-0.023	15
5	2	existing	3A	Q25th	0.0386	1.22	1145 (4.4%)	1.4	-0.005	9.4
5	2	existing	4A	5C	0.0368	1.2	1255 (3.9%)	1.7	0.002	5
5	2	existing	5A	5C	0.0323	1.36	1983 (4.9%)	2.4	0.005	5
5	2	existing	6A	5C	0.0318	1.4	1624 (4.4%)	6.5	-0.011	5
5	2	existing	7	5C	0.0277	1.6	2813 (4.4%)	4.1	0.011	5
5	2	existing	8	5C	0.0277	1.74	3926 (4%)	5.2	0.020	5
3	2	existing	1A	None	0.0484	None	0 (0%)	0.0	0.000	None
3	2	existing	2A	5C	0.0481	1.05	254 (1.7%)	0.1	-0.006	5
3	2	existing	3A	Q25th	0.047	1.42	1316 (5.1%)	2.0	-0.056	9.4
3	2	existing	4A	5C	0.0459	1.37	1317 (4.2%)	2.7	-0.043	5
3	2	existing	5A	5C	0.0432	1.67	2314 (6%)	2.9	-0.063	5
3	2	existing	6A	5C	0.0429	1.82	1567 (4.4%)	12.1	-0.114	5
3	2	existing	7	5C	0.0405	2.23	3159 (5.2%)	5.7	-0.093	5
3	2	existing	8	Q25th	0.0405	1.24	1638 (1.8%)	1.0	-0.001	-14.4
1.5	2	existing	1A	None	0.0539	None	0 (0%)	0.0	0.000	None
1.5	2	existing	2A	5C	0.0538	1.1	294 (1.9%)	0.9	-0.021	5
1.5	2	existing	3A	5C	0.0533	1.48	526 (2%)	9.0	-0.123	5
1.5	2	existing	4A	None	0.0527	None	0 (0%)	0.0	0.000	None
1.5	2	existing	5A	None	0.0513	None	0 (0%)	0.0	0.000	None
1.5	2	existing	6A	None	0.0512	None	0 (0%)	0.0	0.000	None
1.5	2	existing	7	None	0.05	None	0 (0%)	0.0	0.000	None
1.5	2	existing	8	None	0.05	None	0 (0%)	0.0	0.000	None
0.6	2	existing	1A	None	0.0573	None	0 (0%)	0.0	0.000	None
0.6	2	existing	2A	5C	0.0572	1.15	258 (1.7%)	2.2	-0.042	5
0.6	2	existing	3A	None	0.057	None	0 (0%)	0.0	0.000	None
0.6	2	existing	4A	None	0.0568	None	0 (0%)	0.0	0.000	None
0.6	2	existing	5A	None	0.0562	None	0 (0%)	0.0	0.000	None
0.6	2	existing	6A	None	0.0562	None	0 (0%)	0.0	0.000	None
0.6	2	existing	7	None	0.0557	None	0 (0%)	0.0	0.000	None
0.6	2	existing	8	None	0.0557	None	0 (0%)	0.0	0.000	None
10	1	new	1A	None	0.0151	None	0 (0%)	0.0	0.000	None
10	1	new	2A	Q25th	0.0144	1.25	176 (1.1%)	0.8	0.000	15
10	1	new	3A	Q25th	0.0144	1.16	422 (1.5%)	0.5	0.005	9.4
10	1	new	4A	Inf2	0.0144	1.29	582 (1.6%)	0.8	0.008	4.2 / 14.4
10	1	new	5A	Inf2	0.0144	1.43	981 (2.2%)	0.5	0.011	4.2 / 14.4

10	1	new	6A	Inf2	0.0144	1.52	807 (2%)	3.3	0.003	4.2 / 14.4
10	1	new	7	Inf2	0.0144	1.77	1520 (2.2%)	1.1	0.016	4.2 / 14.4
10	1	new	8	Inf2	0.0144	1.93	2039 (1.9%)	1.4	0.023	4.2 / 14.4
7	1	new	1A	None	0.0235	None	0 (0%)	0.0	0.000	None
7	1	new	2A	Q25th	0.023	1.29	279 (1.8%)	1.1	-0.006	15
7	1	new	3A	Q25th	0.0211	1.19	611 (2.3%)	1.0	0.003	9.4
7	1	new	4A	5C	0.0192	1.16	656 (1.9%)	0.8	0.007	5
7	1	new	5A	5C	0.0144	1.27	869 (2.0%)	0.6	0.009	5
7	1	new	6A	5C	0.0144	1.3	746 (1.9%)	2.7	0.003	5
7	1	new	7	5C	0.0144	1.46	1424 (2.2%)	1.6	0.013	5
7	1	new	8	5C	0.0144	1.56	1987 (1.9%)	2.1	0.019	5
5	1	new	1A	None	0.0292	None	0 (0%)	0.0	0.000	None
5	1	new	2A	Q25th	0.0288	1.3	353 (2.3%)	-0.8	-0.013	15
5	1	new	3A	Q25th	0.0274	1.21	822 (3.1%)	0.5	-0.001	9.4
5	1	new	4A	5C	0.0261	1.19	905 (2.7%)	0.8	0.003	5
5	1	new	5A	5C	0.0226	1.34	1437 (3.5%)	1.0	0.006	5
5	1	new	6A	5C	0.0223	1.38	1165 (3.1%)	4.9	-0.006	5
5	1	new	7	5C	0.0192	1.56	1977 (3.1%)	2.9	0.010	5
5	1	new	8	5C	0.0192	1.69	2723 (2.7%)	3.5	0.017	5
3	1	new	1A	None	0.0348	None	0 (0%)	0.0	0.000	None
3	1	new	2A	5C	0.0346	1.04	210 (1.4%)	-0.2	-0.002	5
3	1	new	3A	Q25th	0.0338	1.36	1134 (4.3%)	0.3	-0.027	9.4
3	1	new	4A	5C	0.0329	1.31	1099 (3.3%)	0.9	-0.020	5
3	1	new	5A	5C	0.0309	1.58	1931 (4.7%)	0.5	-0.029	5
3	1	new	6A	5C	0.0307	1.69	1384 (3.7%)	9.2	-0.060	5
3	1	new	7	5C	0.0288	2.02	2551 (4.1%)	3.8	-0.041	5
3	1	new	8	Q25th	0.0288	1.22	1980 (2.0%)	3.4	0.003	-14.4
1.5	1	new	1A	None	0.039	None	0 (0%)	0.0	0.000	None
1.5	1	new	2A	5C	0.0389	1.08	248 (1.6%)	0.7	-0.011	5
1.5	1	new	3A	5C	0.0385	1.4	650 (2.5%)	7.9	-0.069	5
1.5	1	new	4A	None	0.0381	None	0 (0%)	0.0	0.000	None
1.5	1	new	5A	Q25th	0.0371	2.22	153 (0.4%)	15.4	-0.200	1.1
1.5	1	new	6A	None	0.037	None	0 (0%)	0.0	0.000	None
1.5	1	new	7	None	0.036	None	0 (0%)	0.0	0.000	None
1.5	1	new	8	None	0.036	None	0 (0%)	0.0	0.000	None
0.6	1	new	1A	None	0.0416	None	0 (0%)	0.0	0.000	None
0.6	1	new	2A	5C	0.0415	1.12	238 (1.5%)	1.9	-0.023	5
0.6	1	new	3A	None	0.0414	None	0 (0%)	0.0	0.000	None
0.6	1	new	4A	None	0.0412	None	0 (0%)	0.0	0.000	None
0.6	1	new	5A	None	0.0408	None	0 (0%)	0.0	0.000	None
0.6	1	new	6A	None	0.0407	None	0 (0%)	0.0	0.000	None

0.6	1	new	7	None	0.0404	None	0 (0%)	0.0	0.000	None
0.6	1	new	8	None	0.0404	None	0 (0%)	0.0	0.000	None
10	2	new	1A	None	0.0144	None	0 (0%)	0.0	0.000	None
10	2	new	2A	Q25th	0.0144	1.24	177 (1.2%)	0.9	0.002	15
10	2	new	3A	Inf2	0.0144	1.3	436 (1.6%)	1.2	0.005	9.2 / 16.2
10	2	new	4A	Inf2	0.0144	1.42	699 (2.0%)	1.6	0.011	9.2 / 16.2
10	2	new	5A	Inf2	0.0144	1.63	1055 (2.3%)	1.4	0.013	9.2 / 16.2
10	2	new	6A	Inf2	0.0144	1.83	875 (2.1%)	5.1	0.000	9.2 / 16.2
10	2	new	7	Inf2	0.0144	2.25	1697 (2.3%)	1.9	0.017	9.2 / 16.2
10	2	new	8	Inf2	0.0144	2.47	2646 (2.4%)	2.6	0.024	9.2 / 16.2
7	2	new	1A	None	0.0172	None	0 (0%)	0.0	0.000	None
7	2	new	2A	Q25th	0.0166	1.27	203 (1.4%)	1.3	-0.001	15
7	2	new	3A	Q25th	0.0144	1.17	427 (1.7%)	0.9	0.005	9.4
7	2	new	4A	Inf2	0.0144	1.25	528 (1.6%)	1.2	0.007	1.6 / 13.5
7	2	new	5A	5C	0.0144	1.25	890 (2.2%)	0.9	0.010	5
7	2	new	6A	5C	0.0144	1.29	753 (2.0%)	2.5	0.005	5
7	2	new	7	5C	0.0144	1.43	1472 (2.2%)	1.7	0.015	5
7	2	new	8	Inf2	0.0144	1.85	2333 (2.3%)	2.6	0.021	1.6 / 13.5
5	2	new	1A	None	0.0247	None	0 (0%)	0.0	0.000	None
5	2	new	2A	Q25th	0.0242	1.29	293 (2%)	1.4	-0.007	15
5	2	new	3A	Q25th	0.0224	1.2	658 (2.6%)	1.7	0.003	9.4
5	2	new	4A	5C	0.0206	1.17	704 (2.3%)	1.5	0.006	5
5	2	new	5A	5C	0.016	1.29	982 (2.5%)	1.5	0.009	5
5	2	new	6A	5C	0.0156	1.33	822 (2.3%)	3.6	0.002	5
5	2	new	7	5C	0.0144	1.49	1512 (2.5%)	2.4	0.013	5
5	2	new	8	5C	0.0144	1.6	2077 (2.2%)	3.2	0.018	5
3	2	new	1A	None	0.0321	None	0 (0%)	0.0	0.000	None
3	2	new	2A	Q25th	0.0318	1.37	347 (2.4%)	-1.3	-0.024	15
3	2	new	3A	Q25th	0.0307	1.25	908 (3.7%)	1.4	-0.009	9.4
3	2	new	4A	5C	0.0297	1.23	1046 (3.5%)	1.6	-0.003	5
3	2	new	5A	5C	0.0269	1.41	1708 (4.6%)	2.5	-0.004	5
3	2	new	6A	5C	0.0267	1.46	1382 (4.1%)	7.4	-0.020	5
3	2	new	7	5C	0.0242	1.66	2570 (4.4%)	4.6	0.000	5
3	2	new	8	5C	0.0242	1.93	1867 (2.1%)	7.6	-0.002	5
1.5	2	new	1A	None	0.0377	None	0 (0%)	0.0	0.000	None
1.5	2	new	2A	5C	0.0375	1.07	224 (1.6%)	0.5	-0.008	5
1.5	2	new	3A	Q25th	0.037	1.82	864 (3.5%)	9.2	-0.121	9.4
1.5	2	new	4A	5C	0.0365	1.76	685 (2.3%)	9.7	-0.109	5
1.5	2	new	5A	Q25th	0.0351	1.61	887 (2.4%)	8.9	-0.076	1.1
1.5	2	new	6A	Q25th	0.035	1.61	41 (0.1%)	16.8	-0.099	-0.6
1.5	2	new	7	None	0.0337	None	0 (0%)	0.0	0.000	None

1.5	2	new	8	None	0.0337	None	0 (0%)	0.0	0.000	None
0.6	2	new	1A	None	0.041	None	0 (0%)	0.0	0.000	None
0.6	2	new	2A	5C	0.041	1.11	224 (1.5%)	1.7	-0.020	5
0.6	2	new	3A	None	0.0408	None	0 (0%)	0.0	0.000	None
0.6	2	new	4A	None	0.0405	None	0 (0%)	0.0	0.000	None
0.6	2	new	5A	None	0.04	None	0 (0%)	0.0	0.000	None
0.6	2	new	6A	None	0.0399	None	0 (0%)	0.0	0.000	None
0.6	2	new	7	None	0.0395	None	0 (0%)	0.0	0.000	None
0.6	2	new	8	None	0.0395	None	0 (0%)	0.0	0.000	None
Note, in climate zone 4A, cut-off temperatures were identical between the 5°C and Q25th strategies. The best strategy is indicated as 5°C in these cases, but this is exactly equivalent to the Q25th strategy.										

Table D-2 Results for recommended cut-off types, 62.2-2013 fan airflows, FSM, energy savings (kWh), changes in relative exposure (%) and AER (hr^{-1}), and cut-off temperature (°C). Negative changes reflect increases in exposure and AER, and positive changes reflect decreases.