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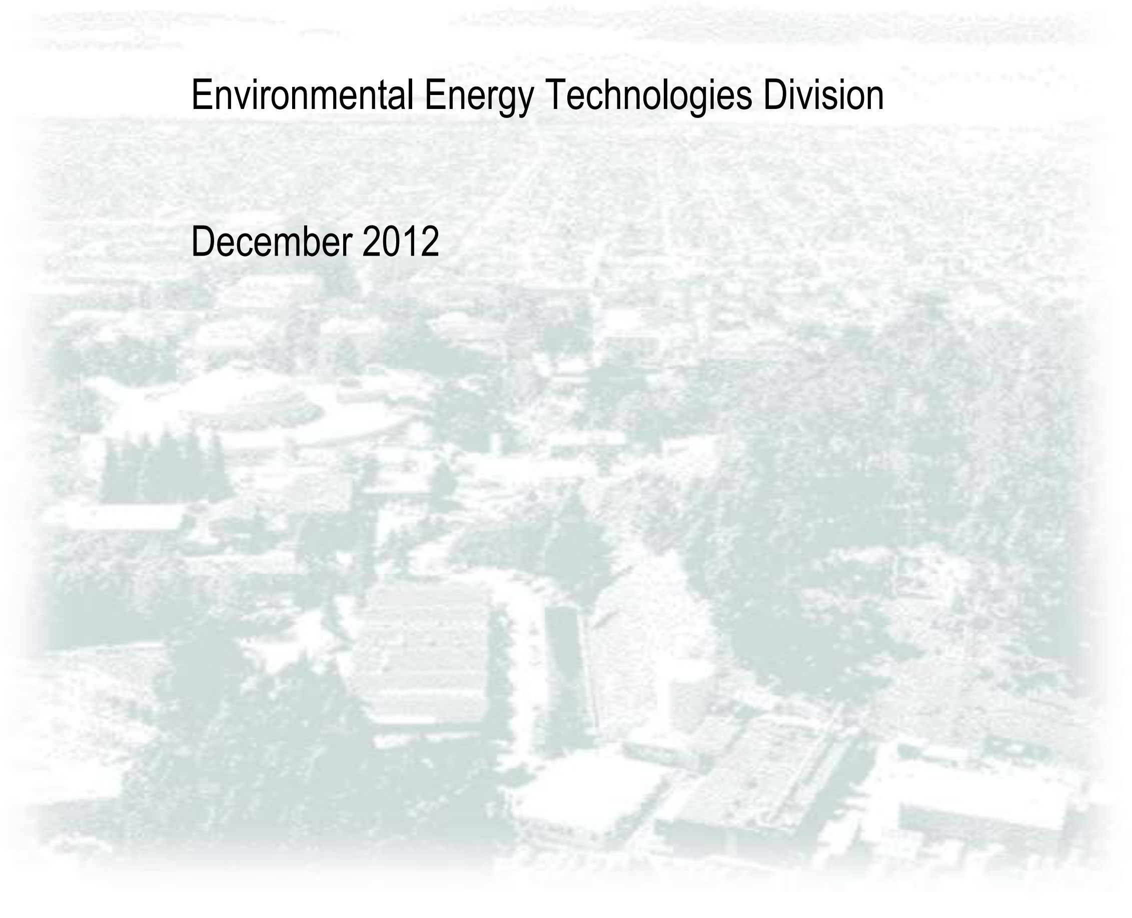

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Contents

ABSTRACT

Whole-house ventilation systems are becoming commonplace in new construction, remodeling/renovation, and weatherization projects, driven by combinations of specific requirements for indoor air quality (IAQ), health, and compliance with standards, such as ASHRAE 62.2. At the same time we wish to reduce the energy use in homes and therefore minimize the energy used to provide ventilation. This study examined several approaches to reducing the energy requirements of providing acceptable IAQ in residential buildings. Two approaches were taken. The first used RIVEC – the Residential Integrated VEntilation Controller – a prototype ventilation controller that aims to deliver whole-house ventilation rates that comply with ventilation standards, for the minimum use of energy. The second used passive and hybrid ventilation systems, rather than mechanical systems, to provide whole-house ventilation.

Computer simulations were performed for four typical whole-house ventilation systems, both with and without RIVEC, so that the energy and IAQ impacts of RIVEC could be compared. Three passive ventilation strategies were also simulated to assess their energy and IAQ potential to provide whole-house ventilation. The above simulations were carried out for 16 California climate zones, three envelope leakage levels, and three house designs.

The results showed that RIVEC could typically reduce the energy penalty from adding whole-house ventilation (including fan energy and the space-conditioning energy used to temper the ventilation air) by more than 40%, without compromising long-term chronic or short-term acute exposures. Critical and average peak power loads were reduced as a consequence of using RIVEC. The passive systems could also meet chronic and acute standards, but uncontrolled over-ventilation during extreme weather resulted in excess energy use. This study also demonstrated that controls for passive systems could ameliorate some of this excess energy use. However, more work needs to be done to optimize and demonstrate passive system controls.

KEYWORDS

Residential Ventilation, Ventilation Controller, ASHRAE Standard 62.2, California Title 24, Passive Ventilation

1. INTRODUCTION

Indoor air quality (IAQ) is a complex result of occupant activities, human responses, source emission, and contaminant removal. The key issues for which one can set requirements are usually ventilation and source control. To set those requirements often requires an understanding of the materials and processes typically found in houses and the operational strategies of their occupants.

Newer homes have become more airtight to reduce heating and air-conditioning use. Consequently they need ventilation systems to maintain IAQ. In response, building codes and standards such as ASHRAE Standard 62.2 (2010) increasingly require homes to have mechanical ventilation to provide acceptable IAQ. Generally whole-house exhaust or supply fans are used as they offer a cheap and simple engineering solution. However, these mechanical fans are usually operated for 24-hours per day and are not optimized for energy efficiency. Although there are some provisions for intermittent system operation, the standards basically assume that there will be a constant ventilation rate from a purpose-provided mechanical ventilation system, for every hour of the day.

The cost of providing mechanical ventilation, however, changes because of weather and the price (or value) of energy. Furthermore, the benefits of providing mechanical ventilation can vary during the day because of the operation of other devices which incidentally provide whole-house mechanical ventilation (for example, vented clothes dryers and kitchen range hoods), or the presence of outdoor air pollutants such as ozone or particulates. However, an integrated approach to looking at residential IAQ is usually lacking. The operating costs and air quality issues can be optimized by using a controller for the whole-house ventilation system that can ventilate at different times of day in response to changing energy and IAQ impacts.

This study uses simulations to evaluate a prototype Residential Integrated VEntilation Controller (RIVEC) that optimizes these operating costs and air quality issues. The control algorithms for RIVEC are optimized and additional control facilities, such as occupancy are developed.

An alternative to mechanical whole-house ventilation is passive ventilation. Natural driving forces such as wind and the stack effect are used instead of electrically driven fans and blowers to move ventilation air. Hybrid ventilation combines components from both mechanical and passive ventilation systems. This study also uses simulations to assess residential, whole-house passive ventilation systems, as well as hybrid systems that incorporate RIVEC.

2. BACKGROUND

RIVEC is a dynamic ventilation controller that attempts to address two opportunities to reduce energy consumption from residential ventilation:

1. optimization of ventilation rates relative to ASHRAE Standard 62.2 - the only standard with guidelines for residential ventilation rates in the United States – by maximizing IAQ while minimizing energy consumption and maintaining compliance with ASHRAE 62.2

2. demand response – the shifting (and stripping) of loads on the power distribution grids at times of peak power demand.

Residential Ventilation Standards

In its simplest form ASHRAE Standard 62.2 specifies minimum continuous, mechanical, whole-house ventilation at a rate, $Q_{62.2}$, based on the size and occupancy of the house:

$$Q_{62.2} = 0.05 \cdot A_{floor} + 3.5\left(N_{br} + 1\right) \tag{1}$$

Where:

$Q_{62.2}$ = fan airflow rate [L/s]

A_{floor} = occupied floor area of the home [m^2]

N_{br} = number of bedrooms

Although the standard specifies certain performance conditions for mechanical ventilation, it also allows the use of dual-purpose fans (one fan can simultaneously provide both local exhaust and continuous whole-house ventilation) to meet whole-house requirements, and provides a methodology for using time-varying mechanical ventilation. However, ASHRAE Standard 62.2 does not account for the fact that, in a typical occupied house, a variety of activities independent of the whole-house ventilation system will ventilate the home. This can include the use of kitchen and bathroom exhaust fans, economizers and clothes dryers. In addition, the standard does not take into account that it can be beneficial, for energy-efficiency or air quality reasons, to temporarily reduce or eliminate mechanical ventilation at certain times of the day. A potential solution is to use a ventilation controller that can monitor all of the mechanical ventilation flows in a home and adjust the whole-house ventilation rate accordingly. RIVEC takes advantage of exogenous mechanical ventilation and shifts the operation of the ventilation system to desirable times of day by controlling the whole-house ventilation fan. The control method is based on original work by Sherman et al. (2009) during work carried out for the California Energy Commission's Energy Innovations and Small Grant Program.

The Energy/Indoor Air Quality Tradeoff

The ventilation, heating and air-conditioning of buildings is one of the dominant uses of energy in the United States. Residential buildings account for 22% of total US energy consumption, with 54% of this attributed to space heating and cooling (DOE, 2011). The energy demand of existing technologies poses several key problems. Resultant CO_2 emissions are contributing to climate change and global warming. Diminishing fossil fuel reserves mean that the US has to seek alternative energy sources while maximizing the energy conversion of existing supplies. As the demand for fuel increases so does its economic cost. Recent residential construction methods have yielded tighter building envelopes that can save energy, but also create a potential for under-ventilation (Offerman, 2009, Sherman and Dickerhoff, 1994, Sherman and Matson, 2002). This under-ventilation directly and negatively impinges on IAQ by not removing contaminants from the indoor environment.

While energy conservation and efficiency are important, it is recognized that measures implemented must not be at the cost of IAQ. The World Health Organization (WHO) notes that the indoor environment represents an important microenvironment in which people spend a significant portion of their time each day. In general people spend 80% to 90% of their time in an indoor environment living, working or commuting (Bower, 1995, ASHRAE, 2005, Spengler et al., 1982, Szalai, 1972). As a result, indoor air pollution is more likely to contribute to population exposure than the outdoor environment (World Health Organisation, 2005).

Ventilation of buildings introduces outdoor air into the occupied zone while displacing stale indoor air, thus improving IAQ. However, the outdoor air typically needs to be conditioned to meet thermal comfort requirements, so ventilation increases the heating and/or cooling load of the building. Clearly a balance needs to be met between energy consumption and IAQ.

Peak Energy Demand and Demand Response

'Peak energy demand' refers to the time of day when loads on the gas and electricity distribution infrastructures reach a maximum. During the winter months this is typically between 4am and 8am when external temperatures are at their coldest and the heating demand is greatest. During the summer months the demand tends to reach a maximum between 2pm and 6pm when the cooling demand is greatest and consequently the air conditioning load is the highest.

During these peak periods the extra demand on the grid is met by increasing capacity via the operation of power plants with a higher marginal cost and higher CO_2 emissions. This increases the generation cost for each kilowatt-hour for the utility company. The cost is then passed down to the consumer in increased utility rates. Failure to increase the capacity of the grid can lead to wide scale blackouts when the energy demand outstrips the supply.

'Demand response' refers to mechanisms that reduce the peak energy demand by moving loads to non-peak periods of the day (shifting) or reducing the total demand during the peak period (shedding). At its most simple, an example of demand response would be to run the domestic household washing machine late in the evening when electricity demand is low. Utility companies in the US are beginning to offer tariff-based incentives to consumers to help reduce peak energy demand and hence cost. An example of this is *Time of Use* (TOU) schemes where a schedule is set by the utility company offering cheaper energy prices during off peak times and more expensive energy during peak times. The aim is to encourage consumers to shift their main energy use to periods when energy generation is less expensive and the overall demand may be met more easily.

Passive and Hybrid Ventilation

An alternative to mechanical whole-house ventilation is passive ventilation. Passive ventilation has been used for centuries and is still popular in many European countries as a way to provide local exhaust and whole-house ventilation. It exploits natural driving forces such as wind and the stack effect to bring ventilation air inside a house. The advantages of passive ventilation over mechanical ventilation include lower (and sometimes zero) operating costs, energy consumption, and maintenance requirements. However, because the airflow rate depends on these naturally occurring forces, it can be highly variable.

Control measures can be used to regulate the airflow to prevent over- and under-ventilation. When mechanical control measures are combined with natural ventilation the result is a hybrid ventilation system. The aim of such systems is to provide the control associated with mechanical ventilation and the reduced energy and maintenance costs of passive ventilation.

3. THE RESIDENTIAL INTEGRATED VENTILATION CONTROLLER (RIVEC)

The Residential Integrated VEntilation Controller (RIVEC) is a dynamic control system for whole-house ventilation fans. It aims to address the IAQ/energy tradeoff and peak demand problems associated with ventilation, while maintaining compliance with ASHRAE Standard 62.2. RIVEC can also be incorporated into hybrid ventilation systems. RIVEC coordinates the operation of a whole-house exhaust fan in response to other exhaust and supply fans in the house, peak energy demand, and potentially lowering ventilation rates when there are high levels of outdoor pollutants, e.g., ozone (ARB, 2005). The system is designed to be used in various climates and programmed according to the house size and number of people in a home.

RIVEC is designed to meet the intent of California's 2012 Title 24 (CEC, 2008b) requirements for residential ventilation. RIVEC is also designed to manage all compliant residential ventilation systems that the California Energy Commission reviewed in developing the Title 24 requirements.

Currently ASHRAE Standard 62.2 only allows the use of intermittent ventilation operating to a *fixed* schedule. This prohibits the use of RIVEC as it operates to a *non*-fixed, adaptive schedule based on levels of relative dose, exposure and occupancy. Therefore, further amendments to the standard are being proposed as a result of the RIVEC work.

Sherman et al. (2009) created and field-tested a prototype of the RIVEC controller in a warm climate (Central Valley, California) in a home with three bathroom fans, a kitchen fan, a dryer exhaust, and an economizer. This field test, reported to the California Energy Commission, demonstrated that the air quality was maintained above the minimum requirement of ASHRAE Standard 62.2.

The RIVEC controller is intended to manage any mechanical ventilation system that is installed, meeting whole-house mechanical ventilation requirements at minimum energy cost. The controller can do this by shifting the ventilation load of the whole-house mechanical ventilation system off peak and taking into account auxiliary mechanical ventilation by other systems (Sherman and Walker, 2011).

To accomplish this, the controller must be able to regulate the state of the installed mechanical ventilation system and to sense when all significant exogenous mechanical ventilation systems are operating. For example, if the 75 *L/s* household clothes dryer is running it is likely that the minimum whole-house ventilation rate will be satisfied by this alone, and so the RIVEC controlled device does not need to operate at the same time once the indoor air quality has reached a desirable level. To prevent rapid cycling or switching of the whole-house ventilation fan, the controller makes decisions at fixed times. If the switching decision time is too long then we will see over- and under-shooting of target dose and exposure. A reasonable balance between rapid cycling and overshooting is to use time steps of 10 minutes between decisions about turning the fan on or off. Note that the observations of operation of other air moving devices and the calculations of relative dose and exposure are performed on a much shorter time scale. This is so that short duration fan operation (such as bathroom exhaust fans) can be captured and to ensure more accurate estimations of relative dose and exposure compared to using longer times between calculations.

To perform the necessary calculations, the controller must be programmed with a variety of specific house and system parameters:

- Floor area of house
- Volume of house
- Number of bedrooms (a surrogate for the number of occupants)
- Infiltration contribution to ventilation
- Target ventilation rate in A_{eq} in air changes per hour (the first four parameters above are used to calculate A_{eq})
- Peak hours for turning off the whole-house fan
- Airflow capacity of the whole-house mechanical ventilation system
- Airflow capacities of each exogenous mechanical ventilation system (e.g. bathroom fans, kitchen range hoods and clothes dryers)

RIVEC uses these inputs in an algorithm to estimate the dose and exposure for the home relative to that provided by a continuously operating fan that complies with ASHRAE Standard 62.2. The fan controlled by RIVEC must be oversized to compensate for the times while the fan is off. Previous work by Sherman and Walker (2011) has shown that a fan sized to 125% of the 62.2 minimum ventilation rate is required for a fan that will be switched off for at least four hours every day (the peak energy demand period).

RIVEC Metrics – Relative Dose and Exposure

The ASHRAE Standard 62.2 minimum whole-house airflow rate from Equation (1) gives us a fixed target whole-house airflow rate that can be used together with an assumed constant pollutant generation rate to calculate an occupant’s exposure to a pollutant. The dynamic controller needs to achieve the same or lower exposure to demonstrate equivalent IAQ. Standard 62.2 also requires that kitchens and bathrooms be equipped with exhaust fans that can provide ventilation of at least 50 L/s and 25 L/s, respectively. The standard does not specify a minimum operating time for these fans as it does for whole-house mechanical ventilation.

It is important to point out the standard is very flexible about how one may achieve the minimum ventilation - supply ventilation, exhaust ventilation, balanced ventilation or appropriate combinations thereof may be used. Systems that ventilate incidentally (such as bath fans, clothes dryers, or economizers) may be counted towards the total provided they meet the basic requirements. RIVEC makes use of this flexibility to improve the energy efficiency of the system.

RIVEC implements the concept of *efficacy* and intermittent ventilation which allows time shifting of ventilation. Using this approach ventilation can be shifted away from times of high cost or high outdoor pollution towards times when it is cheaper and more effective.

The intermittent ventilation algorithm in ASHRAE 62.2 is a simplified procedure (that makes it amenable to using tables in the standard) more details of which can be found in Sherman (2006). The RIVEC controller generalizes that method.

The temporal ventilation effectiveness or efficacy is the ratio of the ventilation one would need if the rate were constant to the actual ventilation. For our simple case it links the equivalent (or desired) steady-state ventilation rate (A_{eq}, which is equivalent to $Q_{62.2}$ plus some infiltration contribution), the actual (or needed) rates of over-ventilation and under-ventilation (A_{high} and A_{low}) and the fraction of time that the space is under-ventilated (f_{low}):

$$\varepsilon = \frac{A_{eq}}{f_{low} A_{low} + (1 - f_{low}) A_{high}} \tag{2}$$

If we have an independent measure of the efficacy, we can use it and Equation 1 to determine the range of acceptable design parameters. The solution is expressed in dimensionless terms involving the efficacy and two other parameters:

$$\varepsilon = \frac{1 - f_{low}^2 \mathrm{N} \cdot \coth(\mathrm{N}/\varepsilon)}{1 - f_{low}^2} \tag{3}$$

where “coth” in Equation (3) is the hyperbolic cotangent and the nominal turn-over, *N*, is defined as follows:

$$\mathrm{N} \equiv \frac{(A_{eq} - A_{low}) \cdot T_{cycle}}{2} \tag{4}$$

where T_{cycle} is the length of a cycle (typically this will be the sum of the time of operation at higher and lower airflows). We are going to address the case of most interest for peak demand reduction, which is called *Notch Ventilation*. In this case we assume that the ventilation system is shut off for 4 hours per day at times of peak loads or to avoid high concentrations of outdoor pollutants (e.g. ozone) and on continuously for the remaining 20 hours. Using the rates of ASHRAE 62.2 and typical housing values, the efficacy is then 96%. This implies that for the notch ventilation case, we must have a mechanical ventilation system sized 25% larger than if it were being used continuously.

The intermittent ventilation algorithms cited above are based on the effective ventilation work of Sherman and Wilson (1986). In order to generalize the intermittent ventilation to ventilation rates that may vary in real time, we need to refer to that work to develop an equivalent way to determine IAQ. We do that by following Sherman and Wilson to determine the equivalent exposure to a general but constant (or uncorrelated) contaminant exposure. For such a case the key parameter is the inverse of the building air change rate, or the *turn-over time*, τ_e:

$$\tau_e(t) = \int_{-\infty}^{t} e^{\int_{t}^{t'} A(t'')dt''} dt' \tag{5}$$

Where *A(t)* is the instantaneous air change rate. If we have a target constant ventilation rate that leads to the appropriate absolute exposure then the *relative exposure*, R, is just the product of that and the instantaneous turn-over:

$$R(t) = A_{eq} \tau_e(t) \tag{6}$$

The intermittent ventilation equations are based on providing the same steady-state dose over any cycle time of interest. The *relative dose, d,* is the average relative exposure over any steady-state cycle, T:

$$d = \frac{1}{T} \int_{0}^{T} R(t)dt = 1/\varepsilon = A_{eq} \bar{\tau} \tag{7}$$

The efficacy used in the intermittent ventilation equations is just then the inverse of the relative dose and can be related to the average turn-over time for the period.

The equations above are useful for continuous unbounded data, but for the purpose of computer simulation it is more useful to use a recursive formula for discrete data. We can rewrite the expression for turn-over time as follows:

$$\tau_i = \frac{1 - e^{-A_i \Delta t}}{A_i} + \tau_{i-1} e^{-A_i \Delta t} \tag{8}$$

We can also write an expression for the (recursive) discrete relative dose based on a 24-hour control cycle. This value varies only a few percent from unity for notch ventilation.

$$d_i = A_{eq} \tau_i (1 - e^{-\Delta t / 24hrs}) + d_{i-1} e^{-\Delta t / 24hrs} \tag{9}$$

The RIVEC control algorithm determines when to turn the whole house fan on and off to maintain a relative dose of unity and control relative exposure extremes.

Occupied Relative Dose and Exposure

While the household occupants are absent they are no longer being exposed to the indoor contaminants of the home. This requires slight modifications to how we calculate the relative dose and exposure, or rather, the *occupied* relative dose and exposure. As relative exposure is governed by pollutants significant over acute time periods, when the occupant is absent the occupied relative exposure simply drops to zero. The relative exposure levels in the house must continue to be tracked so that the appropriate level of relative exposure can be calculated for when the occupants return. However, as relative dose deals with pollutants significant over chronic time periods the calculation needs to account for the periods when the occupants are absent. Equation (9) for the relative dose at time i is based on the relative dose at time $i-1$ and the current relative exposure. For unoccupied times, unity is used instead of the actual relative exposure:

$$d_{unoccupied,i} = 1 \cdot \left(1 - e^{-\frac{\Delta t}{24hrs}} \right) + d_{unoccupied,i-1} e^{-\frac{\Delta t}{24hrs}} \tag{10}$$

When the building is occupied once more the dose calculation returns to normal using Equation (9). As occupancy was tracked in the simulations contained within this study, henceforth the terms *relative dose* and *relative exposure* will refer to *occupied relative dose* and *occupied relative exposure*.

RIVEC Control Algorithm

The RIVEC control algorithm was first outlined by Sherman and Walker (2011) and Sherman et al. (2009). This work develops the control algorithm to reflect results from those reports. The main modifications are to eliminate the pre-peak and post-peak shoulder periods, to remove minimum and maximum ventilation rates and to include occupancy sensing. These measures were implemented to both simplify the control algorithm and make it more robust for a larger range of houses with different ventilation strategies.

The new algorithm recognizes only two time periods - a peak energy demand period and a non-peak energy demand period (i.e. normal operation). During normal operation the whole-house ventilation strategy is controlled by an upper limit to the relative exposure and the relative dose. The values of these upper limits depend on the occupancy of the house. While the house is occupied the relative exposure is limited to a maximum of 0.95. The relative dose is limited to a maximum of 1.0. If the dose and exposure are less than these values the RIVEC controller switches off the ventilation device. A decision is made by the controller every 10 minutes. As soon as either of these values has been exceeded the ventilation device is switched back on. During unoccupied periods the algorithm controls on a limit to the relative exposure only, defined by:

$$R_{lim} = 1 + 4 \cdot \left(\frac{1 - X}{1 + Y} \right) \tag{11}$$

Where:

$$X = \frac{Q_{62.2}}{Q_{RIVEC}} \tag{12}$$

$$Y = \frac{Q_{infiltration}}{Q_{RIVEC}} \tag{13}$$

$Q_{62.2}$ [L/s] is the minimum whole-house ventilation airflow rate as defined by ASHRAE Standard 62.2. (see Equation (1)) Q_{RIVEC} [L/s] is the airflow rate of the RIVEC controlled fan.

$R_{\lim}$ is a function of the power of the RIVEC fan. As Q_{RIVEC} increases, X and Y both approach zero, and so $R_{\lim}$ approaches 5. Conversely, as Q_{RIVEC} approaches $Q_{62.2}$, X and Y both approach 1, and $R_{\lim}$ approaches 1. This means that a more powerful RIVEC-controlled fan allows the house to build up higher concentrations during unoccupied times. The whole-house ventilation system can be off for longer periods while the house is unoccupied, as the inhabitants will not be exposed to the higher levels of indoor contaminants, while limiting the peak levels that a returning occupant is exposed to at the beginning of the occupancy period.

During the peak energy demand period the RIVEC controller switches off the ventilation device. It will only turn back on if the relative exposure exceeds the above exposure limit, $R_{\lim}$. The peak periods are hardcoded into the controller. For this study 4 am until 8 am was used for heating days, and 2 pm until 6 pm was used for cooling days. As heating and cooling set points were used to control the furnace and the air-conditioning, very occasionally there would be both heating and cooling on the same day. The RIVEC algorithm allows there to be no more than one peak period with zero whole-house ventilation on these days to avoid the situation where the ventilation system would be off for two four-hour periods (eight hours total) in any 24-hour period.

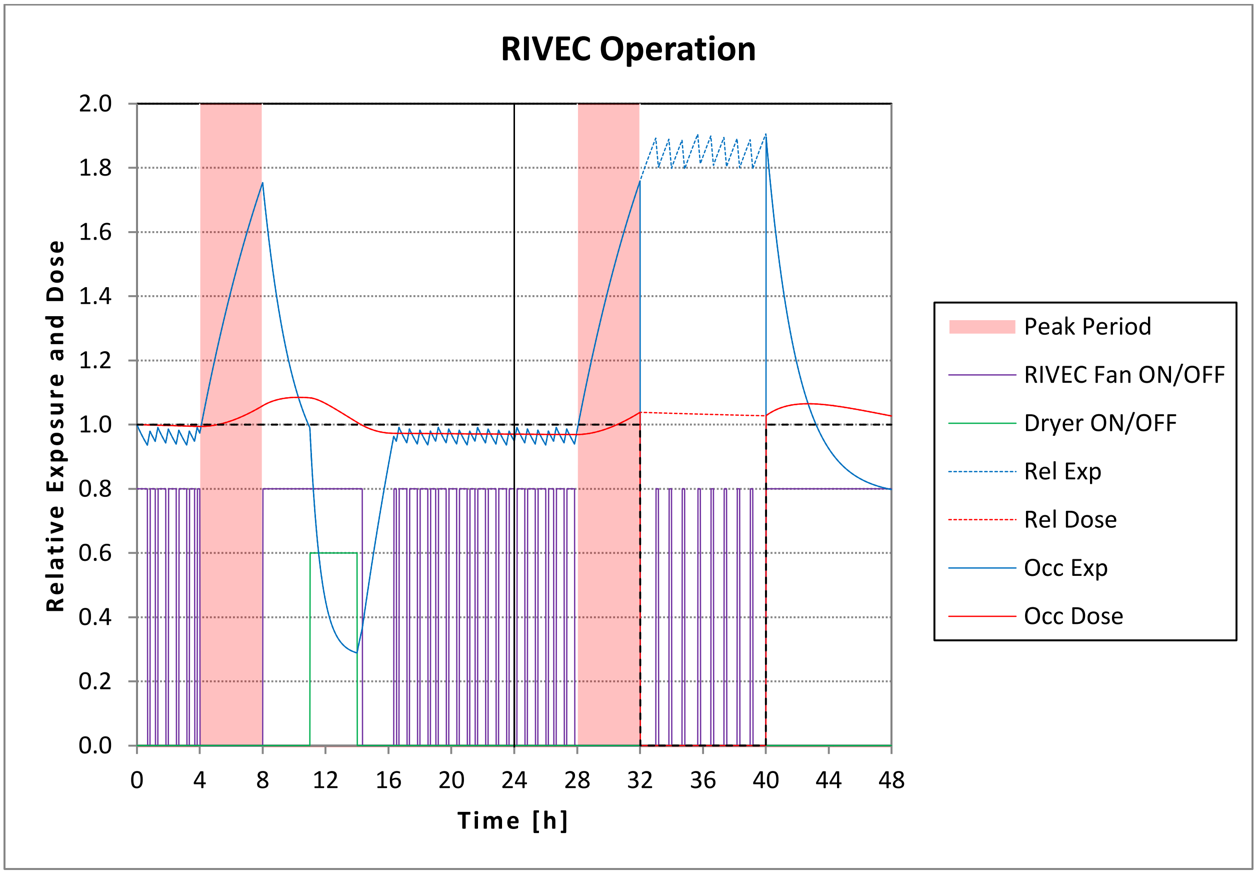


Figure 1: Relative Dose and Exposure controlled by RIVEC, accounting for dryer operation

Figure 1 illustrates an example of RIVEC operation over a 48-hour period. During the occupied period (shown by the dashed black line, where 1 = occupied and 0 = unoccupied) the relative dose is limited to

1.00 and relative exposure is limited to 0.95 by cycling the RIVEC fan (green line). Between 4 am and 8 am (the peak heating energy period shown by the red line) the RIVEC fan is forced to be off and the dose and exposure rise. Once the peak period is over the RIVEC fan turns back on to bring the dose and exposure back down to the controlled levels. The clothes dryer (purple line) turns on at 11 am on day 1 (Sunday) and runs for three hours. The dryer operation is sensed by the RIVEC controller and so the estimated dose and exposure levels inside the house are reduced by the RIVEC algorithms. Thus the RIVEC controller turns off the whole-house RIVEC fan sooner than if the dryer operation had not been sensed and accounted for in the RIVEC algorithms. During the unoccupied period on day 2 (Monday) the occupied exposure drops to zero and the occupied dose remains constant. The relative exposure is controlled at the exposure limit given by Equation (11). Once the building becomes occupied again at the end of the working day, the occupied exposure and dose are calculated as usual. For the two-day period the RIVEC is operating for 1,630 minutes i.e. 57% of the time as opposed to 100% for a continuously operating fan. Over the period of a whole week this will be less due to the bias of unoccupied weekdays to occupied weekends.

Meeting Chronic and Acute IAQ Levels with Intermittent Ventilation

Sherman et al. (2011) presented a method for assessing the viability of intermittent whole-house ventilation strategies to meet ASHRAE Standard 62.2, by analyzing relative indoor pollutant concentrations of contaminants thought to be important over acute timescales. Maximum permissible relative exposures were identified as 4.7 for 1-h time periods (set by NO_2), 5.4 for 8-h time periods (set by Formaldehyde) and 2.5 for 24-h time periods (set by $PM_{2.5}$) (Table 1). For this report the lowest acute-to-chronic ratio represents the maximum relative exposure allowed, i.e., 2.5.

For the whole-house mechanical ventilation systems the relative exposures are controlled by RIVEC so that these maximum values are never reached. However, for the passive stack simulations there is no control on relative exposure and so the maximum levels need to be considered.

Table 1: Maximum concentrations of indoor contaminants allowed by standards and guidelines (Sherman et al., 2011)

COMPOUND	**Concentration [$\mu g/m^3$]**			
	Chronic	**24 h**	**8 h**	**1 h**
Acetaldehyde*	3.7E+00	-	3.0E+02	4.7E+02
Acrolein*	2.0E-02	-	7.0E-01	2.5E+00
Acrylonitrile	3.0E-02	-	-	-
Benzene*	3.4E-01	-	-	1.3E+03
Benzyl Chloride	2.0E-01	-	5.2E+03	2.4E+02
Butadiene, 1,3-*	6.0E-02	-	-	-
Cadmium	2.4E-03	-	-	-
Carbon Tetrachloride	2.4E-01	-	-	1.9E+03
Chloroform	2.0E+00	-	-	1.5E+02
Chromium	6.7E-05	-	-	-
Dichlorobenzene, 1,4-*	9.1E-01	-	4.5E+04	-
Dichloropropane,1,2-	4.0E+00	-	3.5E+05	-
Ethanol	-	-	1.9E+06	-
Ethylbenzene	4.0E+00	-	-	-
Formaldehyde*	**1.7E+00**	-	**9.0E+00**	5.5E+01
Hexachlorobutadiene	4.5E-01	-	-	-
Methylene Chloride	1.0E+01	-	-	1.4E+04
Naphthalene*	2.9E-01	-	5.0E+04	-
NO2*	**4.0E+01**	-	-	**1.9E+02**
PM2.5*	**1.0E+01**	**2.5E+01**	-	-
Tetrachloroethane, 1,1,2,2-	1.7E-01	-	3.5E+04	-
Tetrachlorothene	1.7E+00	-	-	2.0E+04
Vinyl Chloride	1.3E-01	-	-	1.8E+06
Lowest Acute-to-Chronic Ratio [-]	**-**	**2.5**	**5.4**	**4.7**

** Compounds identified as key contaminants (Logue et al., 2010). Lowest acute-to-chronic ratio highlighted in boxes (or relative exposure in the context of this report).*

Infiltration Credit

The 2010 edition of ASHRAE Standard 62.2 has a default infiltration credit of 10 L/s per 100 m^2 (2 cfm/100 ft^2) of floor space. This infiltration credit is used to reduce the installed mechanical fan airflow requirements for the whole-house ventilation system. It does not apply to local exhaust ventilation.

The RIVEC controller cannot sense the contribution of infiltration towards ventilation, but this contribution still needs to be accounted for in the calculations. In this study we used the ASHRAE 62.2 2010 approach of including the default infiltration credit of 10 L/s per 100 m^2 in the target whole-house ventilation rate (A_{eq}). This was to allow easy comparison with the existing ASHRAE 62.2 standard.

Consequently, for the simulations we used the default infiltration credit as a baseline ventilation rate in the RIVEC calculations.

Addendum N to ASHRAE 62.2 has recently been published. It revises the standard to:

- explicitly include the default in the total airflow requirements
- include the full infiltration credit (rather than the current half-credit)
- update the weather factors (including adding many hundreds more weather stations), and
- move all the required calculations into Standard 62.2 thus eliminating the references to Standards 119 and 136.

The difference between the old ASHRAE 62.2 method and new Addendum N in terms of total ventilation rate is usually small, but tighter homes will require more mechanical ventilation.

It is envisioned that the RIVEC controller will have a preprogrammed look-up table that will allow the commissioning agent to set the appropriate ventilation credit by selecting a building envelope leakage and weather factor. The infiltration credit will be a fixed value dependent on climate zone and independent of local fluctuations in the weather data.

4. WHOLE-HOUSE VENTILATION STRATEGIES

This study simulates six residential whole-house ventilation strategies:

1. Whole-house exhaust
2. Heat Recovery Ventilator (HRV)
3. Central Fan Integrated Supply (CFIS) combined with a whole-house exhaust fan
4. Air-side economizer combined with a whole-house exhaust fan
5. Passive stack ventilation
6. Hybrid ventilation

The first four are purely mechanical systems which can incorporate RIVEC. RIVEC can be incorporated into the hybrid system, but not the passive system which by definition, has no mechanical control. The passive system is included in this study as an alternative to mechanical ventilation.

Mechanical Ventilation Strategies

The following four mechanical ventilation strategies are those typically found in new homes that are ASHRAE 62.2 compliant. For this study, simulations were conducted with and without RIVEC incorporated into the systems. This was to assess the performance of RIVEC at reducing ventilation energy costs while attempting to maintain IAQ.

Strategy 1: Whole-House Exhaust

In this system the primary whole-house ventilation system is a simple exhaust fan (Figure 2). When the exhaust fan operates it depressurizes the house. Outside air is drawn in through cracks, leaks and openings in the building envelope. In the default configuration, the fan runs continuously at the minimum rate specified by ASHRAE Standard 62.2.from Equation (1). Under RIVEC operation, RIVEC turns the whole-house exhaust fan on or off.

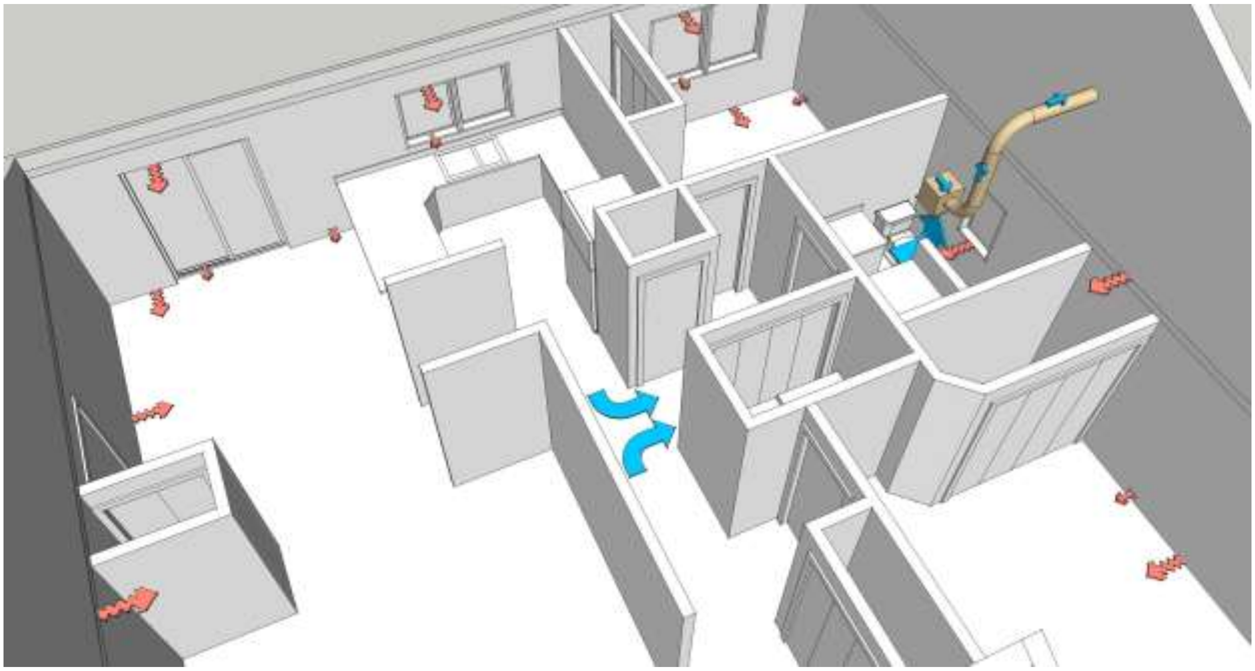


Figure 2; Mechanical whole-house exhaust system

Strategy 2: Heat Recovery Ventilator (HRV)

An HRV is a balanced ventilation system that provides heat recovery from the outgoing air to the incoming air using an air-air heat exchanger (Figure 3). The most common installation, and the one we simulated, has the HRV sized significantly larger than the ASHRAE 62.2 rate (e.g. by a factor of 2), and integrated with the forced air system and ductwork. The HRV and the air handler are synchronized. In the default configuration, they both cycle every 30 minutes on a timer to meet the ASHRAE 62.2 minimum airflow rate. Under RIVEC operation, RIVEC controls the HRV.

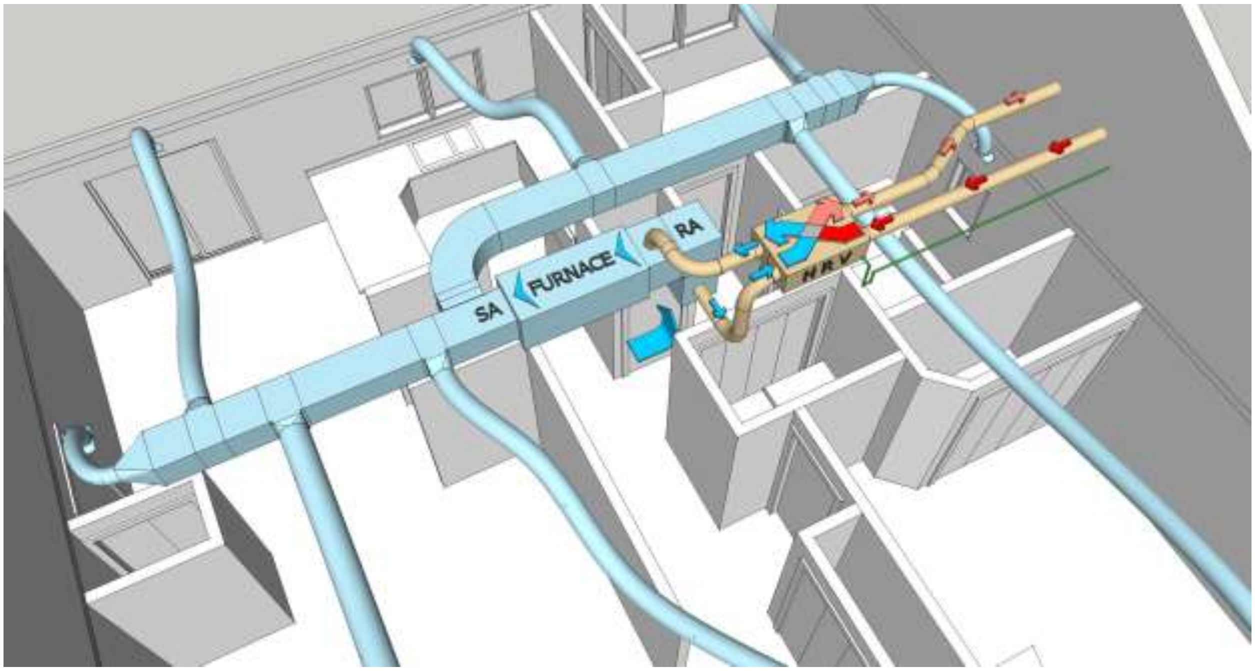


Figure 3: Heat Recovery Ventilator system fully integrated in the force air system

Strategy 3: Central Fan Integrated Supply (CFIS) with Whole-House Exhaust

CFIS uses the air handler to draw outside air into the return via a duct to outside (Figure 4). The outside air is mixed with the return air from the forced air system and distributed throughout the house using the heating/cooling ducts. A damper in the outside air duct opens during air handler operation for heating and cooling. The outside air damper is sized so that when the air handler is operating, the airflow rate from outside meets the ASHRAE Standard 62.2 continuous rate. Because this system does not operate continuously it is not an ASHRAE 62.2 compliant ventilation system. The CFIS is a service that acts in addition to Title 24 or ASHRAE 62.2 requirements and therefore was not under the control of RIVEC. To comply with 62.2 the system operates in conjunction with a continuously operating whole-house exhaust fan. In the default configuration, the whole-house exhaust fan operates continuously. Under RIVEC operation the whole-house fan is controlled by RIVEC.

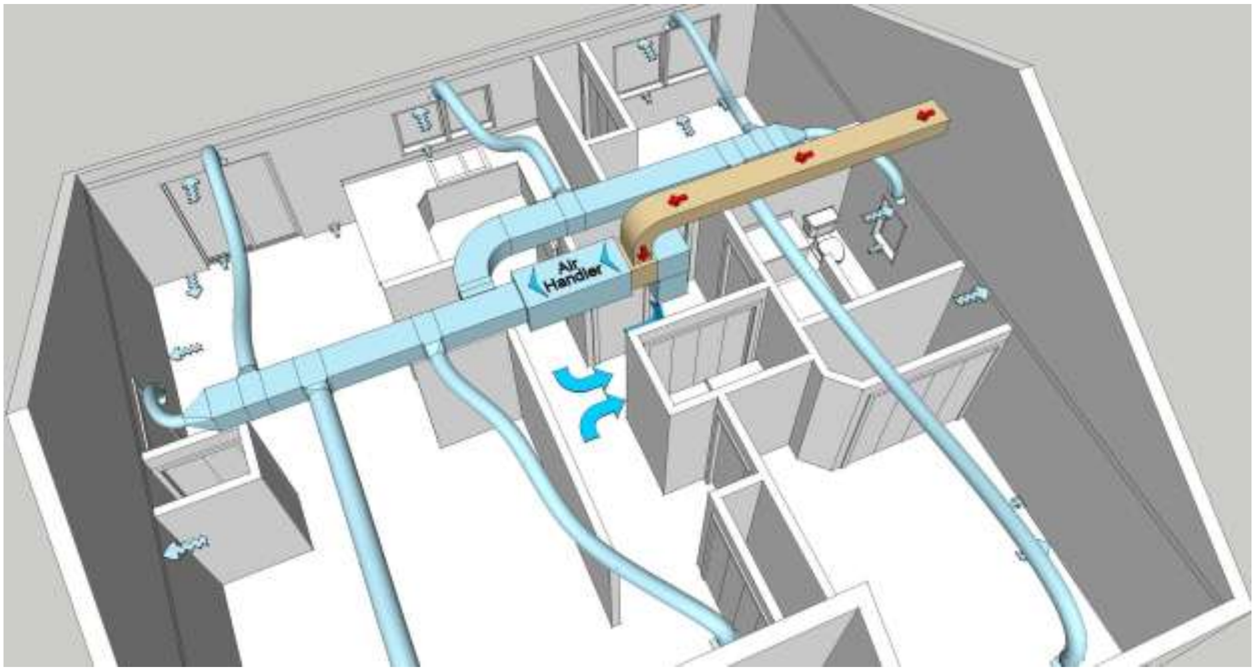


Figure 4: Central Fan Integrated Supply system

Strategy 4: Economizer with Whole-House Exhaust

In the context of this study, economizers are large supply fans that reduce the cooling load of a building by supplying cool nighttime air to the occupied zone in climates with large diurnal temperature swings. In typical residential applications the heating/cooling air handler is used as the economizer fan. A damper opens allowing the economizer to distribute outside air to the occupied zone via the supply ducts. To avoid pressurizing the house, during operation of the economizer a pressure relief opens in the ceiling.

Economizers are used to provide cooling to the house. The ventilation they provide from the increased airflow rates is incidental and also climate-dependent. For this reason the economizer system is combined with a whole-house exhaust fan in order to comply with ASHRAE 62.2. Under the default configuration the whole-house exhaust operates continuously. Under RIVEC operation, the whole-house fan is controlled by RIVEC. RIVEC takes into account the effect on IAQ when the economizer operates, and delays the use of the whole-house exhaust appropriately.

Passive and Hybrid Ventilation Strategies

The next two ventilation strategies are more common in Europe, but there is increasing interest in the United States. *Natural ventilation* utilizes naturally occurring driving forces such as wind and stack effects to achieve the same goal of mechanical ventilation of bringing outside air into the indoor environment. One such method of natural ventilation in residences is *passive stack* ventilation. Another system incorporates both passive and mechanical ventilation. This is known as *hybrid* or *mixed-mode* ventilation.

Strategy 5: Passive Stack Ventilation

Passive stacks are vertical vents inside the house that extend above the roof to outside (Figure 5). They are used to exploit naturally occurring pressure differences to provide ventilation. A combination of stack and wind pressures on a vent causes air to be drawn from the house and expelled outside. Passive stacks can be used to remove indoor contaminants from the room in which the base of the vent is located (usually kitchens and bathrooms), as well as to provide whole-house ventilation.

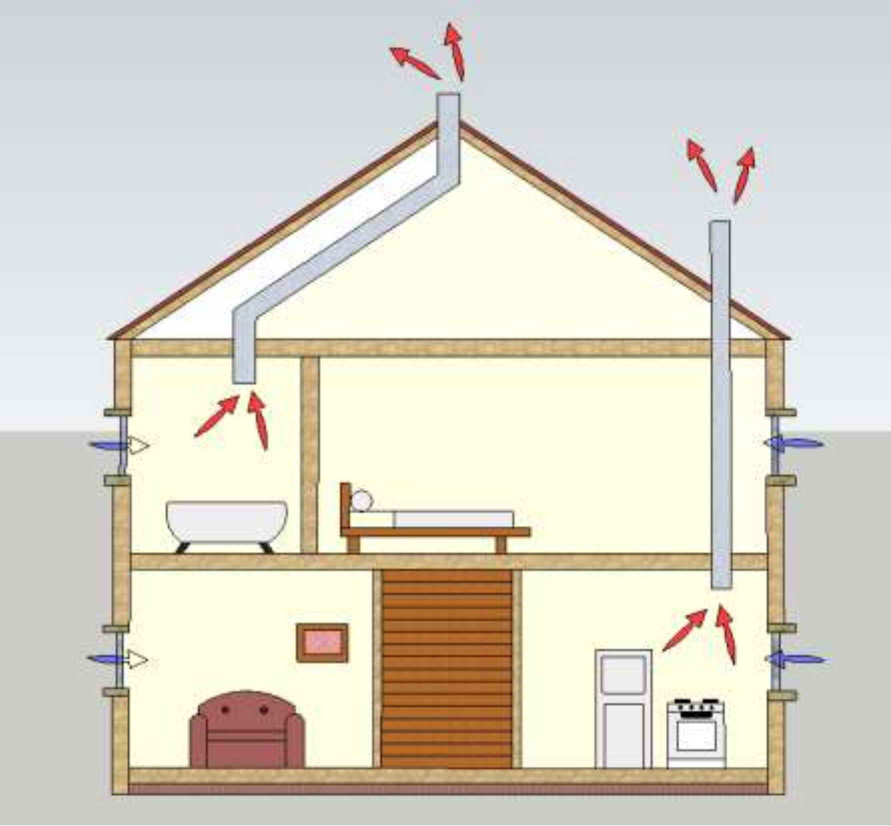


Figure 5: Passive stack ventilation

Passive stack ventilation no mechanical (fan) energy. However, the variable nature of the wind and the outdoor temperature mean that passive stack ventilation is both intermittent and potentially unreliable. Throughout the year there will be times of large, naturally occurring pressure differences resulting in over-ventilation. There will also be times of under-ventilation when these pressure differences are low. It is therefore important to have an appropriately sized passive stack to minimize the times of over and under-ventilation. The airflow rate through the stack can also be augmented to desirable levels via the deployment of control strategies such as flow dampers to limit high ventilation rates, or auxiliary fans to increase low ventilation rates.

This study focuses on the effectiveness of passive stacks to provide whole-house ventilation. For a description of the practical design and installation of passive stacks the reader is referred to Appendix D in Part F of the UK Building Regulations (Office of the Deputy Prime Minister, 2006).

The default configuration uses a passive stack sized to meet ASHRAE 62.2 for at least 80% of the year. The alternative configuration uses an over-sized passive stack that is flow-limited to 125% of the ASHRAE 62.2 mechanical airflow rate. RIVEC is not used.

Strategy 6: Hybrid Ventilation

A hybrid or mixed-mode ventilation system utilizes both mechanical and natural ventilation. To overcome the unpredictable nature of natural ventilation some form of mechanical control is used to regulate the airflow rate. The mechanical and natural components may be used in conjunction with each other or used separately at different times of the day. While acting as a control measure, the mechanical component may be used to regulate the natural ventilation process by restricting the airflow rate during periods of high natural driving forces or to provide additional ventilation at times of low natural driving forces.

The default configuration is an over-sized passive stack which is flow-limited to 100% of the mechanical 62.2 airflow rate. This is combined with a whole-house exhaust fan (62.2 compliant) that is controlled by RIVEC.

Exogenous Mechanical Ventilation

Although there may be only one whole-house system designed and controlled to meet minimum ventilation requirements, there are other pieces of equipment that can have significant impacts on the total mechanical ventilation rate. The RIVEC controller monitors many of these exogenous systems and takes into account their impacts on IAQ, thereby lessening the need for additional mechanical ventilation.

The systems that RIVEC can monitor include:

- clothes dryers - according to ASHRAE 62.2 and building codes, clothes dryers must be vented to outside. When the dryers operate this venting alone is usually sufficient to meet minimum whole-house requirements and thus it may be possible to turn off the whole-house ventilation system when the dryer is operating

- bathroom extract fans – used to control odor and moisture generated in bathrooms. ASHRAE 62.2 prescribes that intermittently operating bathroom fans should have a minimum flow rate of 25 L/s (50 cfm)

- kitchen range hoods – used to control cooking generated indoor pollutants. ASHRAE 62.2 prescribes that intermittently operating kitchen range hoods should have a minimum ventilation rate of 50 L/s (100 cfm).

Households use these fans in different ways, and so their operation needs to be monitored in real-time by RIVEC. Due to the high flow rates they can provide significant ventilation while running. Each of the six whole-house ventilation strategies simulated in this study also included the operation of clothes dryers, bathroom exhaust fans and kitchen range hoods.

5. SIMULATIONS

Seven different residential ventilation strategies were simulated (Table 2). All of the strategies include the exogenous ventilation described above. Each ventilation strategy was simulated for the three house sizes, using the three different air leakages, in all 16 California climate zones.

Strategy 0 is a reference case with no whole-house ventilation system operating. It acts as a baseline for all other cases so that the ventilation energy can be calculated (i.e. the extra energy incurred from adding whole-house ventilation to a home).

Strategies 1 (whole-house exhaust), 3 (CFIS), and 4 (economizer) all had whole-house exhaust fans that were simulated either running continuously (1a, 2a, 4a) or under RIVEC control (1b, 2b, 4b). Strategy 2 (HRV) operated for either the first 30 minutes of every hour (3a), or under RIVEC control (3b).

Strategy 5 (passive stacks) included up to three stacks that were sized to meet the mechanical ASHRAE 62.2 airflow rate for 80% of the year (5a), or oversized and flow limited to 125% of the ASHRAE 62.2 mechanical minimum (5b).

Strategy 6 (hybrid ventilation) consisted of an oversized passive stack that was flow limited to 100% of the ASHRAE 62.2 mechanical minimum, combined with a whole-house exhaust fan, sized to 125% of the ASHRAE 62.2 mechanical minimum, and operating under RIVEC control (6). The passive stacks were mechanically closed whenever the hybrid fan would operate.

Table 2: Simulations for the different ventilation strategies

Strategy	Ventilation System	Simulations
0	**No whole-house ventilation system** • includes infiltration	'Zero' case to be used as a reference for adding whole-house ventilation Exogenous ventilation systems operate as usual
1	**Whole-House Exhaust Fan** • sized to meet the 62.2 minimum airflow rate	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control
2	**Heat Recovery Ventilation (HRV)** • sized to twice the 62.2 minimum airflow rate	HRV operates: a. for 30 minutes every hour b. intermittently under RIVEC control
3	**Central Fan Integrated Supply (CFIS)** • with airflow sized to meet 62.2 • operates whenever the heating or cooling system operates • combined with 62.2 whole-house exhaust fan	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control
4	**Economizer** • using the air handler operating at cooling fan power and airflow rate • combined with 62.2 whole-house exhaust fan	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control
5	**Passive Stack** • up to three passive stacks depending on house size, leakage and climate zone	Passive stacks: a. sized to meet 62.2 for at least 80% of the year b. oversized and mechanically flow limited to 125% of the 62.2 minimum
6	**Hybrid Ventilation** • up to three passive stacks depending on house size, leakage and climate zone • whole-house exhaust fan + RIVEC	Passive stacks oversized and mechanically flow limited to 100% 62.2 minimum. Stacks closed when hybrid fan operates Whole-house exhaust fan sized to meet 125% of the 62.2 minimum and controlled by RIVEC

Building Simulation Tool

The energy consumption and IAQ of the modeled houses was evaluated by minute-by-minute simulations of the heat and mass balances of the home for a year. The airflows, heat transfer, heating and cooling system operation, and energy use were simulated using the REGCAP residential building simulation tool. REGCAP was modified to simulate RIVEC in previous studies (Walker and Sherman, 2008, Sherman and Walker, 2008). The simulation tool has been validated by comparison to measured data in homes in previous studies (Walker et al., 2006). The simulation program treats the attic volume and house volume as two separate well-mixed zones, but connected for airflow and heat transport and includes heating and cooling system airflows. It combines mass transfer, heat transfer and moisture models. The program allows the modeling of distributed envelope leakage and mechanical system airflows for ventilation, heating and cooling, as well as individual localized leaks such as passive stacks. Inputs are building air leakage characteristics (total leakage and leakage distribution), minute-by-minute weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules.

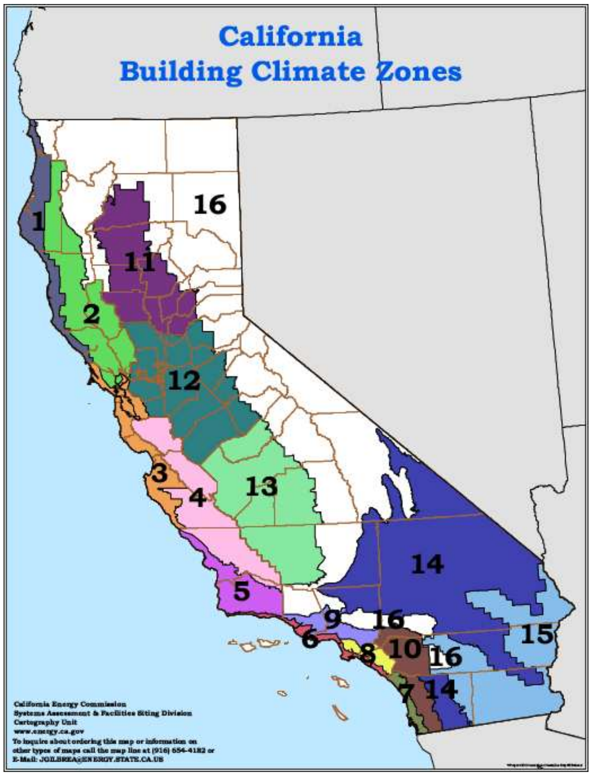
Climates

California climate zones 1 through 16 from the California Energy Commission (CEC, 2008b) were used in the simulations (Figure 6). Weather data was taken from the TMY3 dataset published by NREL (Wilcox and Marion, 2008). TMY3 is hourly data so this was converted into minute-by-minute data using linear interpolation.

Weather data used as input for the simulation modeling was:

• direct solar radiation	[W/m^2]
• total horizontal solar radiation	[W/m^2]
• outdoor air dry-bulb temperature	[°C]
• outdoor air humidity ratio	[g/kg]
• wind speed	[m/s]
• wind direction	[degrees]
• barometric pressure	[kPa]
• cloud cover index	[-]

Climate Zone	City
1	Arcata
2	Santa Rosa
3	Oakland
4	Sunnyvale
5	Santa Maria
6	Los Angeles
7	San Diego
8	El Toro
9	Pasadena
10	Riverside
11	Red Bluff
12	Sacramento
13	Fresno
14	China Lake
15	El Centro
16	Mt. Shasta



California Energy Commission
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Figure 6: CEC Climate Zones for California (CEC, 2008b)

House Size

Three different houses (see Table 3) were simulated to give a good representation of the majority of the housing stock in California. The medium and large houses are based on the CEC's Title 24 prototype simulation houses (Nittler and Wilcox, 2008) Prototype C (see Figure 7) and Prototype D (see Figure 8). The small house is a scaled down version of Prototype C .For the purposes of this report the small house shall be referred to as Prototype B. All houses had uniform 2.5 m (8 ft) ceilings on each floor.

Table 3: Simulation houses and their properties

Name	House Size	Floor Area		Stories	Bedrooms	Bathrooms	Occupants
		[m^2]	[ft^2]				
Prototype B	Small	111	1,200	1	3	2	4
Prototype C	Medium	195	2,100	1	3	3	4
Prototype D	Large	250	2,700	2	4	3	5

While the modeling tool used does not specifically allow for an attached garage, the presence of a garage was accounted for in the building geometry (i.e. adjusted perimeter lengths and first/second story floor areas where appropriate).

Figure 7: Title 24 Housing Prototype C (medium sized simulation house. The small house is a scaled down version of Prototype C) (Nittler and Wilcox, 2008)

Figure 8: Title 24 Housing Prototype D (large sized simulation house) (Nittler and Wilcox, 2008)

House Construction and Envelope Leakage

Each house was simulated with three different envelope leakages based on a study of 108 new homes in California (Offerman, 2009). Envelope leakages used in the simulations were 4.8, 5.2 and 8.6 ACH_{50} (i.e. measured air leakage at 50 Pa). 4.8 ACH_{50} is typical of new construction in California. 5.2 ACH_{50} is typical of homes built since 1992 and 8.6 ACH_{50} is typical of homes built prior to 1986.

Building insulation levels were taken from CEC Title 24 Package D (CEC, 2008a). Exterior surface area for wall insulation scales with floor area and number of stories. A simple rule of thumb developed from measured data from several thousand new homes (based on Building America data (Personal Communication with Building Science Corporation)) and from the simplified Prototype C used in the Title 24 ACM (CEC, 2008a) is that the wall area is typically 1.22 times the floor area for a one-story home and 1.54 times the floor area for a two-story home. Window area was 20% of floor area with windows equally distributed on the four exterior walls. There was 3.7 m^2 (40 ft^2) of door area for each dwelling. All doors were assumed to face north and have a U-factor of 0.50. Floor type was slab-on-grade with a hardwood floor covering. Heat loss through the floor and the slab was calculated as per ASHRAE Fundamentals 2009 using 2.5% summer and 97.5% winter design temperatures from ACCA Manual J (ACCA, 2006). Slab perimeter insulation was taken from the Title 24 ACM, Appendix B (i.e. R7 for climate zone 16).

Heating and cooling equipment sizing (see Table 5) for climate zones 8, 10, 11, 12, 13 and 15 used data from field surveys of Californian homes undertaken in support of Title 24 (personal communication – Rick Chitwood). For all other climate zones the equipment was sized using ACCA Manual J, then oversized as per the size ratio between climate zone 12 from the Chitwood field data and climate zone 12 from Manual J, then finally rounded up to the nearest half ton for cooling. Fan airflow was sized at 16.8 cfm/kBtuh (approximately 27 L/s per kW) for heating and 400 cfm/ton (approximately 55 L/s per kW) for cooling. Fan power was 0.5 W/cfm for both heating and cooling. The heating systems were modeled as 80% AFUE natural gas furnaces and the cooling systems were SEER 13 EER 11 split-system air conditioners with TXV refrigerant flow control. The duct leakage to outside was 6%, split equally between supply leakage (3%) and return leakage (3%).

Heating and cooling equipment was controlled by an automatic thermostat that switched between heating and cooling, as required. Set-up and set-back thermostat settings (see Table 6) were taken from the Title 24 ACM.

Table 4: House Insulation Levels, Standards Table 151-B Component Package D ACM (Appendix B p.5)

Climate Zone	Ceiling			Wall		Ducts Outside Conditioned Space
		Heating Degraded	Cooling Degraded		Degraded	
1	R38	21.6	31.9	R21	17.6	R6
2	R30	18.8	26.1	R13	10.9	R6
3	R30	18.8	26.1	R13	10.9	R6
4	R30	18.8	26.1	R13	10.9	R6
5	R30	18.8	26.1	R13	10.9	R6
6	R30	18.8	26.1	R13	10.9	R4.2
7	R30	18.8	26.1	R13	10.9	R4.2
8	R30	18.8	26.1	R13	10.9	R4.2
9	R30	18.8	26.1	R13	10.9	R6
10	R30	18.8	26.1	R13	10.9	R6
11	R38	21.6	31.9	R19	10.9	R6
12	R38	21.6	31.9	R19	10.9	R6
13	R38	21.6	31.9	R19	10.9	R6
14	R38	21.6	31.9	R21	17.6	R8
15	R38	21.6	31.9	R21	17.6	R8
16	R38	21.6	31.9	R21	17.6	R8

Table 5: Summary of equipment sizing based on Chitwood field data (shaded) and ACCA Manual J calculations (not shaded)

Climate Zone	Climate Name	Cooling [tons/1000 ft^2]	Heating [kBtuh/1000 ft^2]
1	Arcata	0.6	40.5
2	Santa Rosa	1.4	45.0
3	Oakland	1.0	35.9
4	Sunnyvale	0.9	34.8
5	Santa Maria	1.1	41.4
6	LA	1.1	32.0
7	San Diego	1.3	29.8
8	El Toro	2.0	32.6
9	Burbank	1.7	34.8
10	Riverside	2.1	33.0
11	Red Bluff	1.8	39.3
12	Sacramento	1.6	40.5
13	Fresno	2.3	46.6
14	China Lake	1.5	47.9
15	El Centro	2.9	61.7
16	Mt. Shasta	1.1	49.6

Table 6: Thermostat settings for simulations from T24 with heating (4am to 8am) and cooling (2pm to 6pm) peak periods shaded in pale red and blue respectively

Time	Heating		Cooling	
	[°C]	[°F]	[°C]	[°F]
0:00 → 1:00	18.3	65	25.6	78
1:00 → 2:00	18.3	65	25.6	78
2:00 → 3:00	18.3	65	25.6	78
3:00 → 4:00	18.3	65	25.6	78
4:00 → 5:00	18.3	65	25.6	78
5:00 → 6:00	18.3	65	25.6	78
6:00 → 7:00	18.3	65	25.6	78
7:00 → 8:00	20.0	68	28.3	83
8:00 → 9:00	20.0	68	28.3	83
9:00 → 10:00	20.0	68	28.3	83
10:00 → 11:00	20.0	68	28.3	83
11:00 → 12:00	20.0	68	28.3	83
12:00 → 13:00	20.0	68	28.3	83
13:00 → 14:00	20.0	68	27.8	82
14:00 → 15:00	20.0	68	27.2	81
15:00 → 16:00	20.0	68	26.7	80
16:00 → 17:00	20.0	68	26.1	79
17:00 → 18:00	20.0	68	25.6	78
18:00 → 19:00	20.0	68	25.6	78
19:00 → 20:00	20.0	68	25.6	78
20:00 → 21:00	20.0	68	25.6	78
21:00 → 22:00	20.0	68	25.6	78
22:00 → 23:00	20.0	68	25.6	78
23:00 → 0:00	18.3	65	25.6	78

Fenestration

The window Solar Heat Gain Coefficient (SHGC) was 0.4 for climate zones 1 to 16 with the exception of the very hot climate zone 15, where it was 0.35. For all climate zones the window U-Factor was 0.4, maximum total area was 20% of the wall area – spread equally around the four walls. These values were based on Title 24 Residential Compliance Manual Package D. Clear glazing was assumed together with exterior shading of 50%.

Internal Loads

The daily latent gain from moisture generation followed the approach used previously by Walker and Sherman (2006b) and Walker and Sherman (2007). The moisture generation rates were based on ASHRAE Standard 160P (ASHRAE, 2009b) with corrections for kitchen and bathroom generation rates from Emmerich et al. (2005) (see Table 7) that assume that all the kitchen- and bathroom-generated moisture is vented directly to outside using exhaust fans.

The daily sensible gain from lights, appliances, people and other sources used the Title 24 ACM value of 5.9 kWh (20,000 Btu/day) for each dwelling unit plus 0.0044 kWh/day (15 Btu/day) for each square foot of conditioned floor area (see Table 8). Loads were delivered to the occupied zone at a constant rate throughout the day and were not altered for seasonal adjustments.

Table 7: Internal occupancy based moisture generation rates from ASHRAE Standard 160P

Number of Occupants	Total Moisture Generation Rate [kg/day]	Proportion Attributable to Bathing, Cooking and Dishwashing [kg/day]	Net Generation Rate [kg/day]
2	7.8	3.2	4.6
3	12.1	3.6	8.5
4	13.8	4.0	9.8
5	14.7	4.4	10.3

Table 8: Internals loads for the prototype houses based on T24 eq. R3-1 p.3-5 (sensible) and ASHRAE Draft Standard 160P (moisture generation)

House	Number of Occupants	Sensible Load [W]	Moisture Generation [kg/day]
Prototype B (1,200 ft^2)	4	464.0	9.8
Prototype C (2,100 ft^2)	4	628.9	9.8
Prototype D (2,700 ft^2)	5	738.8	10.3

Meeting ASHRAE Standard 62.2 Ventilation Requirements

The simulated houses were designed to have ventilation systems that complied with ASHRAE Standard 62.2. The ventilation systems modeled had to meet a whole-house ventilation rate based on the combination of natural infiltration and mechanical ventilation. Therefore, the target ventilation rate (Q_{eq}) for demonstrating equivalence to ASHRAE 62.2 is the sum of $Q_{62.2}$ (the mechanical component from Equation (1)) and the default infiltration credit Q_{infil} (the assumed natural ventilation component):

$$Q_{eq} = Q_{62.2} + Q_{\inf} \tag{14}$$

Q_{inf} is equal to 10 L/s per 100 m^2 (2 cfm/100 ft^2) in the 2010 edition of ASHRAE Standard 62.2. Q_{eq} is then converted into air changes per hour for use as A_{eq} in the relative dose and exposure calculations (see RIVEC Metrics – Relative Dose and Exposure, above).

The whole-house RIVEC fan airflow rates Q_{RIVEC} need to be 25% larger than $Q_{62.2}$ (not including the default infiltration credit) to account for the four-hour long peak periods when the fan is forced to be off. The airflow rates are summarized in Table 9.

Table 9: Simulation airflow rates for the three test houses

House	**Floor Area**		**Bedrooms**	**Mechanical Target, $Q_{62.2}$**		**Infiltration Credit, Q_{inf}**		**Required Whole-House Flow Rate, Q_{eq}**		**RIVEC Fan Flowrate, Q_{RIVEC}**	
	[m^2]	**[ft^2]**		**[L/s]**	**[cfm]**	**[L/s]**	**[cfm]**	**[L/s]**	**[cfm]**	**[L/s]**	**[cfm]**
Prototype B	111	1,200	3	20	42	11	24	31	66	25	53
Prototype C	195	2,100	3	24	51	20	42	44	93	30	64
Prototype D	250	2,700	4	30	65	25	54	55	119	38	81

Ventilation Equipment

All of the ventilation equipment used in the simulations (Table 10) was taken from the Home Ventilating Institute 2011 Directory (HVI, 2011) and was 62.2 compliant. Note: some fans are multispeed and so can be used for more than one airflow rate.

Table 10: Ventilation equipment for the different simulation houses (HVI, 2011)

House	System	Equipment	Q [L/s]	Q [cfm]	Power [W]	ASE
Prototype B (Small)	Whole-House Fan	*Panasonic FV-08VKM2*	24	50	10.2	-
	RIVEC Fan	*Panasonic, FV-08VKS2*	28	60	11.8	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*NA*	71	150	-	-
	HRV	*VENMAR - AVS Constructo 1.5V*	40	85	64.0	75
Prototype C (Medium)	Whole-House Fan	*Panasonic, FV-08VKS2*	28	60	11.8	-
	RIVEC Fan	*Panasonic, FV-08VKS2*	33	70	14.0	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*NA*	71	150	-	-
	HRV	*GREENTEK - DH 7.15*	56	119	114	75
Prototype D (Large)	Whole-House Fan	*Panasonic, FV-08VKS2*	33	70	14.0	-
	RIVEC Fan	*RenewAire V80*	39	80	16.1	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*NA*	71	150	-	-
	HRV	*BROAN-NUTONE - Maytag*	65	138	124.0	72

Whole-House Exhaust Fans and RIVEC Fans

For all the systems that incorporated a whole-house exhaust fan, the fan was sized to meet the ASHRAE 62.2 minimum. A fan was then chosen from the HVI Directory that met this requirement. As commercially available fans in the US are usually sized to a round number in cfm, some of the whole-house fans had airflow rates that were slightly larger than the 62.2 whole-house minimum. The same applies to the RIVEC fans which were sized to be at least 125% of the 62.2 whole-house minimum.

Heat Recovery Ventilators

A typical application of an HRV system was assumed, where the HRV was connected to the central forced air duct system. The air handler fan was operated at the same time as the HRV for air distribution and to avoid short-circuiting of ventilation air. The HRV unit was sized to twice the 62.2 airflow rate and then operated on a timer for 30 minutes in every hour (Strategy 3a). For the RIVEC simulations the RIVEC controller took over the operation of the HRV unit, thus overriding the timer (Strategy 3b).

The quoted *Apparent Sensible Effectiveness* (ASE) for existing HRVs was used for the energy calculations to determine the temperature of air supplied to the space (T_{to_space}):

$$ASE = \frac{T_{out} - T_{to\_space}}{T_{out} - T_{from\_space}} \tag{15}$$

Central Fan Integrated Supply

The CFIS operated every minute that the forced air system operated (Strategies 2a and 2b). The outside air damper was sized so that ventilation airflow rate supplied by the CFIS met the ASHRAE 62.2 whole-house minimum. Fan power requirements for the air handler remained unchanged from the levels used for standard HVAC operation.

Economizers

The economizers in this study operated when the outdoor temperature was 3.3°C (6°F) or more below the indoor set point and the house temperature was greater than 21°C (70°F) (Strategies 4a and 4b). The HVAC system air handler was used to draw in the outside air and then distribute it to the occupied zone via the heating/cooling ducts. For each house size and climate zone the economizer was sized to match the largest airflow rate and power consumption of the air handler unit. Typically the air handler operated at the cooling airflow rate.

Because the economizer system acts as a large supply fan, to pressure balance the house a hole with area ‘A_{relief}’ was opened in the building envelope:

- $A_{relief} \approx 0.17$ m^2 (1.83 ft^2) for Prototype B
- $A_{relief} \approx 0.31$ m^2 (3.34 ft^2) for Prototype C
- $A_{relief} \approx 0.37$ m^2 (3.98 ft^2) for Prototype D

This hole was sized to result in approximately 2 Pa of house pressurization based on the size of the economizer fan, which was dependent on the HVAC equipment sizing.

Passive Stacks

Two passive stack ventilation strategies were simulated (5a and 5b). For Strategy 5a the passive stacks were sized for each house in each climate zones so that the ASHRAE 62.2 minimum airflow rate was met for 80% of the year. Strategy 5b used larger stacks that met the required flow rate for more of the year, but the total airflow through the stack(s) was mechanically limited to 125% of the 62.2 minimum. This was to reduce over-ventilating during times of large natural driving forces.

The airflow through passive stacks depends on the pressure difference between the inlet and outlet and the airflow resistance. The pressure difference is due to a combination of the stack effect and wind blowing over the top of the stack.

The wind pressure at the stack outlet depends on the pressure coefficient of the stack rain cap/outlet and the wind speed at the outlet. The magnitude of the wind pressure (Δp_w) was modeled dependent on the stack height and rain cap design as well as the wind speed (U):

$$\Delta p_w = \frac{1}{2}\rho C_p U^2 \tag{16}$$

Where: Δp_w = wind pressure [Pa]

ρ = density of air [kg/m^3]

U = wind speed at the rain cap [m/s].

C_p = wind pressure coefficient

The simulations used the pressure coefficient of 0.5 from Haysom and Swinton (1987). The wind pressures on the building use the wind speed at the house eaves as a reference point. The change in wind velocity with height above grade may be significant for passive stacks that protrude above the reference eaves height. In these simulations, the wind speed is corrected using the stack height and an assumed atmospheric boundary layer wind profile exponent taken from the ventilation and infiltration chapter of the ASHRAE Handbook of Fundamentals (2009a). For these simulations it was assumed that the houses were located in urban terrain with a wind pressure exponent of 0.22 and a boundary layer thickness of 370 m. In addition to changing wind speeds compared to the rest of the house, the top of the passive stack was assumed to be above surrounding buildings and other obstacles so a wind shelter factor of 1 (i.e. no shelter) was used. Previous studies by Walker et al. (2006) have found these assumptions produce good estimates of airflow in stacks.

The stack effect is due to differences in hydrostatic pressure between inside and outside the house when the indoor and outdoor air is at different temperatures. The hydrostatic pressure in air depends on its density. The density of air is inversely proportional to its temperature, such that warm air is less dense than cold air. The stack effect was modeled as per the ASHRAE Handbook of Fundamentals

(2009a). With two columns of air (one inside and one outside the house) at different temperatures the resulting pressure difference between the two columns of air is:

$$\Delta p_{se} = g\left(\rho_a - \rho\right)\left(z_2 - z_1\right) \tag{17}$$

Where: Δp_{se} = stack pressure [Pa]
ρ_a = density of ambient air [kg/m^3]
g = acceleration due to gravity = 9.81 m/s^2
z_1 = elevation of bottom of stack [m]
z_2 = elevation of top of stack [m]

The airflow resistance is a combination of inlet, outlet and frictional flow resistance effects as well as the diameter of the stack. The flow resistance effects for the passive stacks in this study were based on a combination of standard engineering fluid mechanics calculations (e.g. Elger et al. (2012)) and the results of laboratory testing of passive stacks by Walker (1989). Stack entry and exit terminal loss coefficients were assumed to be 0.5 (Walker, 1989). The geometry of passive stacks leads to them having a pressure exponent close to 0.5 (this value of 0.5 was assumed in the simulations).

The stacks were sized for the medium envelope leakage house (5.2 ACH$_{50}$), based on previous work by Mortensen et al. (2010). When sizing stacks for larger homes and/or in temperate climates, the required stack diameter can become large enough that in practice it is preferable to use several smaller stacks. This also makes sense from a source control perspective, as the separate stacks can be installed in multiple locations such as bathrooms and kitchens.

Several combinations of up to three passive stacks were used for each house depending on the ventilation requirements of the building. Individual stacks had diameters of 15 and 20 cm. Each passive stack was 3 m in length extending from the topmost ceiling in the occupied zone, through the roof to outside.

Hybrid

The hybrid system consisted of a passive stack for the natural component, with a fan inside the stack for the mechanical component. The fan was controlled by RIVEC. When the RIVEC fan operated the natural flow through the stack was reduced to zero. Only the flow due to the RIVEC fan was simulated. Where multiple stacks were used in the same building, when the RIVEC fan operated the other stacks were closed. The RIVEC fan was assumed to add no flow resistance to the passive stack in which it was located, while it was not operating.

The passive stack was oversized as before, but then to prevent over-ventilation, the total stack flow was restricted to 100% of the ASHRAE 62.2 airflow rate. The RIVEC fan was sized to 125% of the 62.2 minimum, and was still forced to be off during the peak heating and cooling periods.

Calculation of Relative Dose and Exposure for Passive and Hybrid Systems

For the passive and hybrid system it is important to distinguish between the two relative dose and exposure calculations that are occurring during the simulations. RIVEC calculates relative dose and exposure based on its estimates of the infiltration contribution (the assumed ASHRAE 62.2 default infiltration credit), the mechanical fan flows, and the flow in the passive stack. RIVEC uses this calculation of dose and exposure to make a decision to turn on or off the RIVEC fan.

The second dose and exposure calculation uses the total house ventilation rate i.e. the sum of the actual infiltration airflow (as calculated by REGCAP), the mechanical airflows, and the airflow through the passive stacks. This is used to determine the relative dose and exposure of the occupants in the house. Both calculations take into consideration the occupancy schedule.

The passive stack system does not use RIVEC and so the actual airflow of the house is used to calculate the dose and exposure of the occupants. This is to capture correctly the influence of the stack on the building infiltration rate. The hybrid system has a passive stack and RIVEC. So the dose and exposure of the occupants are still calculated using the actual airflow of the house, but the decision to turn on or off the RIVEC fan uses the sum of the infiltration credit, the mechanical flows and the flow in the stack.

Figure 9 shows the calculation of relative dose and exposure for the passive stack ventilation system. The operation of the dryer depressurizes the house and causes the airflow in the stack to decrease. The peak periods are not observed because the system does not use RIVEC, but the occupancy schedule is still observed.

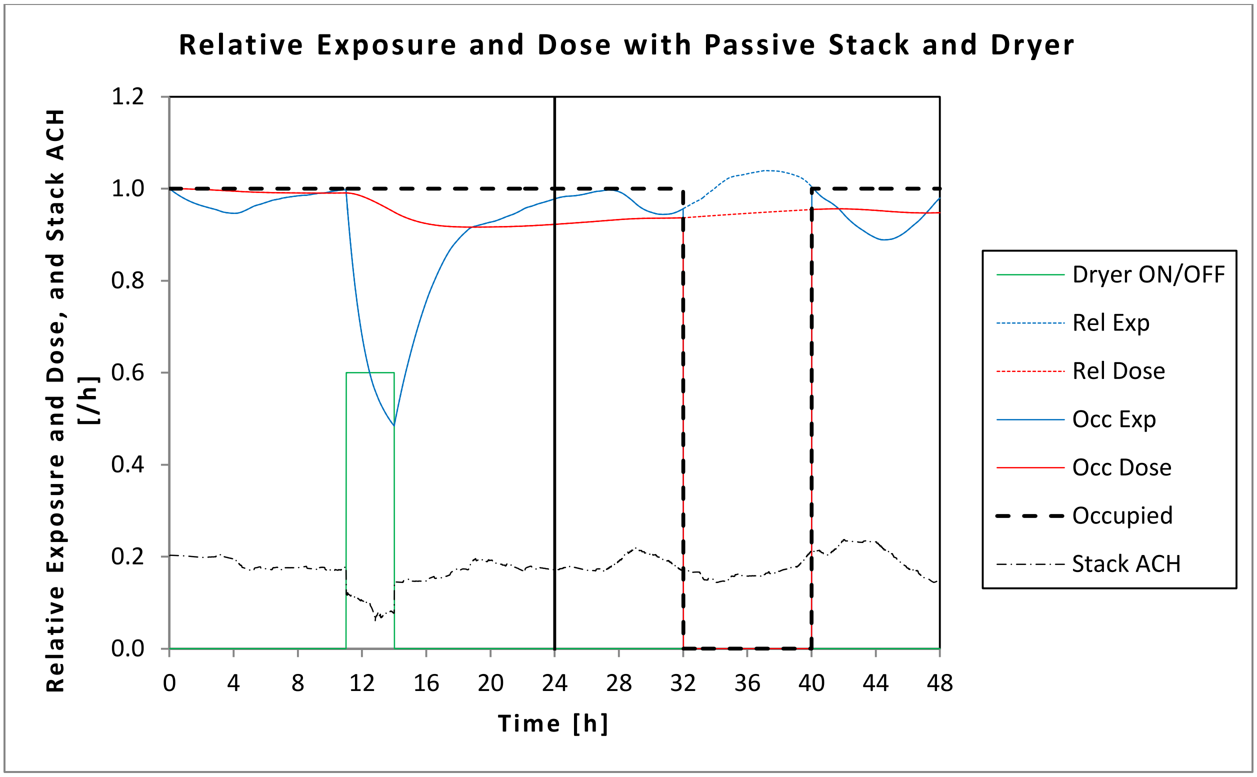


Figure 9: Relative Dose and Exposure with flow through the passive stack

Figure 10 shows the operation of RIVEC for the hybrid system. RIVEC includes the airflow through the stack, the mechanical airflows, and the default infiltration credit in its calculation of relative dose and exposure – used in the decision to turn on or off the RIVEC fan.

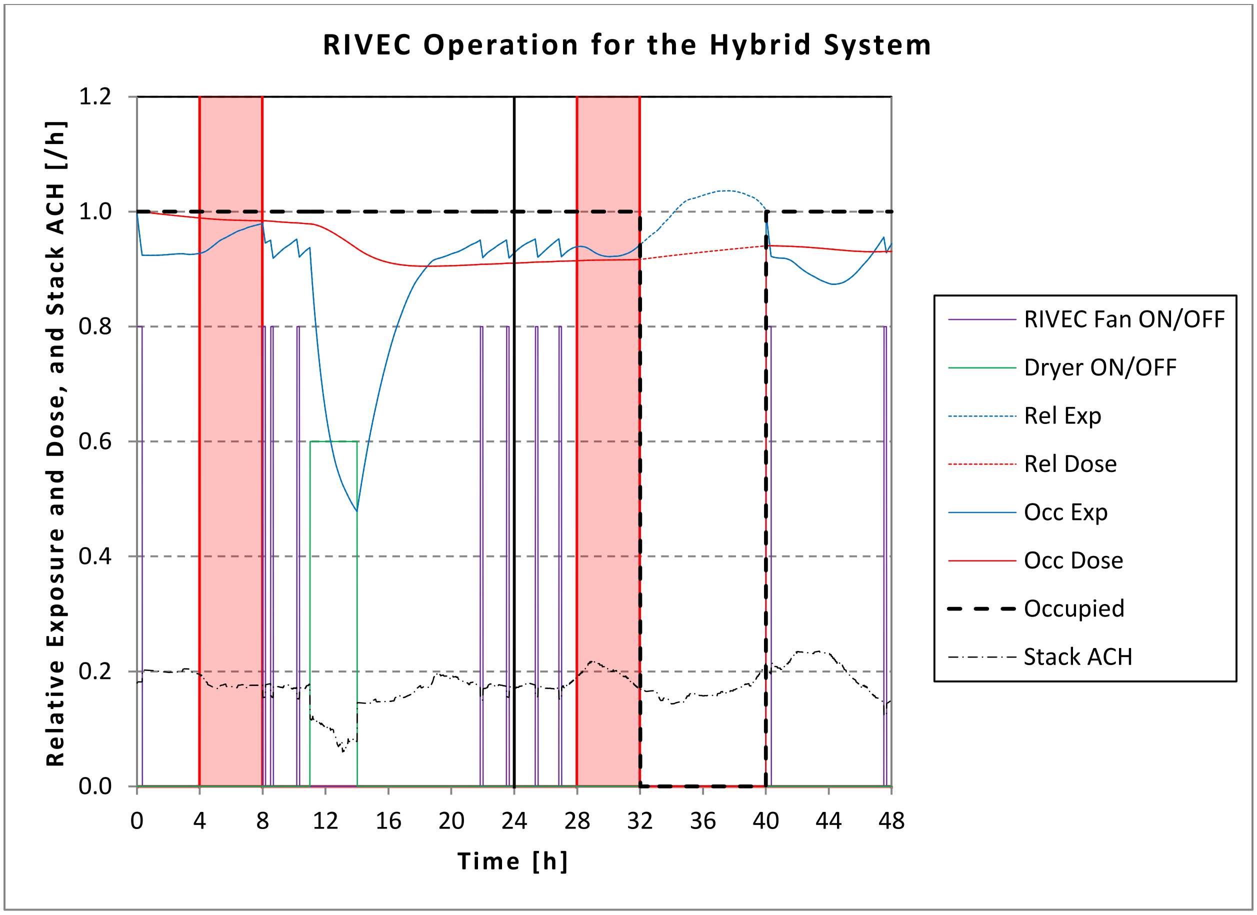


Figure 10: RIVEC operation for the hybrid system with a passive stack

Building Occupancy and Fan Scheduling

The houses were assumed to be unoccupied between 8 am and 4 pm every weekday, and then occupied for the rest of the time. During unoccupied hours the RIVEC algorithm operated under higher upper limits for relative exposure (as given by Equation 8) and still controlled the ventilation system fans. For the RIVEC controller, the dose and exposure calculations were continuous whether the home was occupied or not. However, the calculation of relative dose and exposure for comparison between different ventilation strategies (and comparison to ASHRAE 62.2) used only occupied hours.

Operation of additional ventilation systems was based around the above occupancy schedule. On weekdays one bathroom fan was operated for 30 minutes per occupant every morning (to simulate showering) and again for 10 minutes per occupant in the evening. On weekends the fan run time per occupant was the same as for weekdays, only the times were constrained between 7 am and 11 pm. An algorithm was used to add some degree of daily variability into the bathroom fan schedules. This algorithm did not violate the criteria of a maximum of 40 minutes operation per occupant per day and the general occupancy time periods. The algorithm was used to generate a full yearlong schedule for each of the three home sizes. For each home the same yearlong pre-calculated schedule was used in each simulation. Thus there was variability from day to day as the simulations progressed through the year for each home, but the same variability was used for each simulation. In other words, for any given day of the year for a given house the schedule was the same. The seven different ventilation strategies all used the same schedule to allow the energy results to be directly comparable.

The kitchen range hoods operated for one hour per day between 5.30 pm and 6.30 pm. On weekends there was an additional 30 minutes of operation in the morning between 9.30 am and 10.00 am.

Clothes dryers operated irrespective of occupancy. Two laundry days each week were simulated for the small and medium houses, and three laundry days for the large house. Dryer operation was for three consecutive hours between 11 am and 2 pm to avoid peak times.

6. RESULTS AND DISCUSSION

Whole-house ventilation strategies 1 to 4 are all mechanical ventilation strategies and so will be discussed together. Strategy 5 is passive stack natural ventilation and does not include the RIVEC controller so will be examined separately. Strategy 6 is hybrid ventilation, a combination of passive stack ventilation and RIVEC controlled whole-house mechanical ventilation. It falls under the above two categories so will be compared to the five other strategies when appropriate. Strategy 0 is no whole-house mechanical or natural ventilation and so will be used as a reference for energy calculations.

Strategy 0: Reference Case

The reference case assumed that the heating, cooling and auxiliary ventilation systems (bathroom, kitchen and dryer fans) operated as usual, but without any ASHRAE 62.2 compliant whole-house mechanical ventilation system in place. The energy load from infiltration was included. Total energy used by each house for one year is shown in Table 11. The gas burned by the furnace has been converted into kilowatt-hours using a conversion ratio of 29.3 kWh/therm, so that it may be included in the total energy together with the electrical energy consumed by the air conditioning, air handler and mechanical ventilation system.

Table 11: Energy used by the reference case houses with no 62.2 compliant mechanical ventilation

House	Leakage ACH_{50} [/h]	Total House Energy use per Climate Zone [MWh] or [kWh] x 10^3															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Prototype B	4.8	14.0	10.5	8.6	7.7	9.0	3.4	4.7	4.8	5.5	6.2	10.9	9.5	9.2	10.4	5.9	14.7
	5.2	14.1	10.6	8.6	7.8	9.0	3.4	4.7	4.8	5.5	6.2	11.0	9.5	9.3	10.4	5.9	14.9
	8.6	15.0	11.1	9.1	8.2	9.6	3.5	4.9	5.0	5.8	6.5	11.7	10.0	9.7	11.0	6.1	15.9
Prototype C	4.8	23.1	17.6	14.4	12.9	15.2	5.7	7.9	7.9	9.1	10.2	17.8	15.5	15.1	16.9	9.5	24.8
	5.2	23.3	17.8	14.5	13.0	15.3	5.7	7.9	8.0	9.2	10.3	17.9	15.6	15.2	17.1	9.5	25.0
	8.6	24.9	18.8	15.5	13.8	16.4	6.1	8.4	8.3	9.6	10.8	19.3	16.6	15.9	18.2	10.0	27.1
Prototype D	4.8	28.0	23.8	18.5	16.6	20.3	7.2	9.9	10.1	11.8	13.4	22.1	19.2	19.1	21.4	12.4	32.9
	5.2	28.4	24.0	18.7	16.8	20.6	7.3	10.0	10.2	11.9	13.5	22.4	19.4	19.2	21.7	12.5	33.3
	8.6	31.4	26.0	20.4	18.2	22.6	7.9	10.7	10.8	12.7	14.5	24.6	21.3	20.8	23.9	13.5	37.2

The other simulation results were compared to the reference case to ascertain the additional building energy use caused by introducing a whole-house ventilation system. The difference between the total building energy use with whole-house ventilation and the reference case will be the energy associated with ventilation for that particular strategy.

Occupied Relative Dose and Exposure (RIVEC)

For all RIVEC simulations the relative dose and exposure were controlled by the RIVEC controller algorithm. Table 12 shows the annual mean, and hourly minimum and maximum values for the occupied relative dose and exposure, averaged over all climate zones, house sizes and envelope leakages. Values are shown for both Non-RIVEC (a) and RIVEC (b) cases. To obtain exact equivalence to ASHRAE 62.2 compliant continuous mechanical ventilation systems a mean annual occupied relative dose of 1.00 is required. Values below 1.00 indicate lower dose and exposure, and so better IAQ, than a minimally compliant ASHRAE 62.2 ventilation system.

Table 12: Average annual, and hourly minimum and maximum occupied relative dose and exposure for each mechanical ventilation strategy (all climate zones, house sizes and envelope leakages).

		REFERENCE	WHOLE-HOUSE FAN		HRV		CFIS		ECONOMIZER	
		0	**1a. Non-RIVEC**	**1b. RIVEC**	**2a. Non-RIVEC**	**2b. RIVEC**	**3a. Non-RIVEC**	**3b. RIVEC**	**4a. Non-RIVEC**	**4b. RIVEC**
Occupied Relative Exposure	Min	0.40	0.27	0.28	0.28	0.27	0.27	0.28	0.04	0.04
	Mean	1.75	0.80	0.99	0.83	0.98	0.80	0.99	0.68	0.86
	Max	2.55	0.99	1.86	1.05	2.22	0.99	1.86	0.99	1.87
Occupied Relative Dose	Min	1.00	0.70	0.88	0.76	0.87	0.70	0.88	0.31	0.39
	Mean	1.58	0.85	0.99	0.87	0.98	0.85	0.99	0.75	0.90
	Max	1.96	1.00	1.08	1.00	1.08	1.00	1.08	1.00	1.08

Table 12 shows that the average annual relative dose and exposure for the RIVEC cases never exceed 1.00, indicating that the RIVEC controller is providing equivalent (or better) ventilation compared to ASHRAE Standard 62.2. The Non-RIVEC cases have lower annual means than the RIVEC cases. This indicates over-ventilation. By reducing the operating time of the whole-house fan or HRV, RIVEC reduces the amount of over-ventilation and reduces the ventilation energy used for space conditioning. It should be noted that RIVEC does not know actual infiltration airflow rates. Instead it uses the default infiltration credit from the 2010 edition of ASHRAE 62.2. Therefore these numbers only demonstrate compliance with Standard 62.2.

When using the economizer, the mean annual dose and exposures are approximately 10 to 15% below unity. This is due to the large size and airflow rate of the economizer fan, and suggests that the RIVEC algorithm could be further optimized for use with economizers.

RIVEC Fan Fractional Run Times

Ventilation strategies 1, 3 and 4 (whole-house fan, CFIS and economizer) all used a whole-house, ASHRAE Standard 62.2 compliant fan. This was either operating continuously (525,600 minutes per year) or under RIVEC control. The fractional run time is the amount of time in the year that the RIVEC fan was operating, expressed as a percentage of the total year (see Table 13). The HRV unit was also controlled by RIVEC, but without the RIVEC controller was only operating for 50% of the year (30 minutes every hour). Table 13 shows the runtimes as a percentage of the whole year and of half the year (in parentheses) for the HRV. The Hybrid system used a RIVEC controlled fan to operate as a control measure at times of low naturally induced ventilation.

Table 13: Fractional RIVEC fan runtimes as a percentage of the year. The percentages in parentheses for the HRV unit are the fractional runtimes of half the year

	RIVEC Fan/HRV Fractional Runtimes [% of year]				
	1b. WHOLE-HOUSE EXHAUST	**2b. HRV**	**3b. CFIS + WHOLE-HOUSE EXHAUST**	**4b. ECONOMIZER + WHOLE-HOUSE EXHAUST**	**6. HYBRID**
Min	43	28 (56)	43	30	4
Mean	47	31 (62)	47	36	7
Max	50	33 (66)	50	48	11

For the mechanical ventilation strategies, the RIVEC controller operates the whole-house ventilation fan or HRV for between 30% and 50% of the year depending on ventilation strategy, climate zone etc. This is a significant reduction from the continuously operating 62.2 compliant systems and will have consequential energy savings from reduced space conditioning. The whole-house fan used in the hybrid ventilation strategy operated between 4 and 11% of the year. This is because the passive stack provides adequate ventilation for most of the year. What the hybrid fan does do, however, is prevent the longer periods of high exposure while natural driving forces are low.

Change in Ventilation-Related Energy from using RIVEC

The *ventilation-related energy* is all of the energy associated with adding whole-house ventilation to a house with no whole-house ventilation (for a calendar year in our simulations). This includes electrical fan energy, plus the extra space-conditioning energy from the increased airflow rate in the home. It is calculated by taking the difference in total annual energy between the house with a whole-house ventilation system $E_{\text{Non-RIVEC}}$ and the same house with no whole-house ventilation system E_{Ref} (from Strategy 0 - the reference case) for a given climate zone. We then calculate the impact of RIVEC to reduce the ventilation-related energy using:

$$\text{Change in Ventilation-Related Energy due to RIVEC} = \frac{\left(E_{\text{Non-RIVEC}} - E_{\text{Ref}}\right) - \left(E_{\text{RIVEC}} - E_{\text{Ref}}\right)}{\left(E_{\text{Non-RIVEC}} - E_{\text{Ref}}\right)} \times 100\% \tag{18}$$

Where E_{RIVEC} is the total annual house energy use for a house with a whole-house mechanical ventilation system under RIVEC control.

Figure 11 shows three bars to help explain the concept of ventilation-related energy. Bar 1 is the total energy used by a house with no whole-house ventilation system (the reference case, or Strategy 0), which includes infiltration and the energy required to condition the infiltration air. Bar 2 then shows the increase in total house energy after a whole-house ventilation system has been installed. The difference between bar 1 and bar 2 is the ventilation-related energy. Bar 3 shows the effect of using RIVEC to control the whole-house ventilation system i.e. the ventilation-related energy decreases.

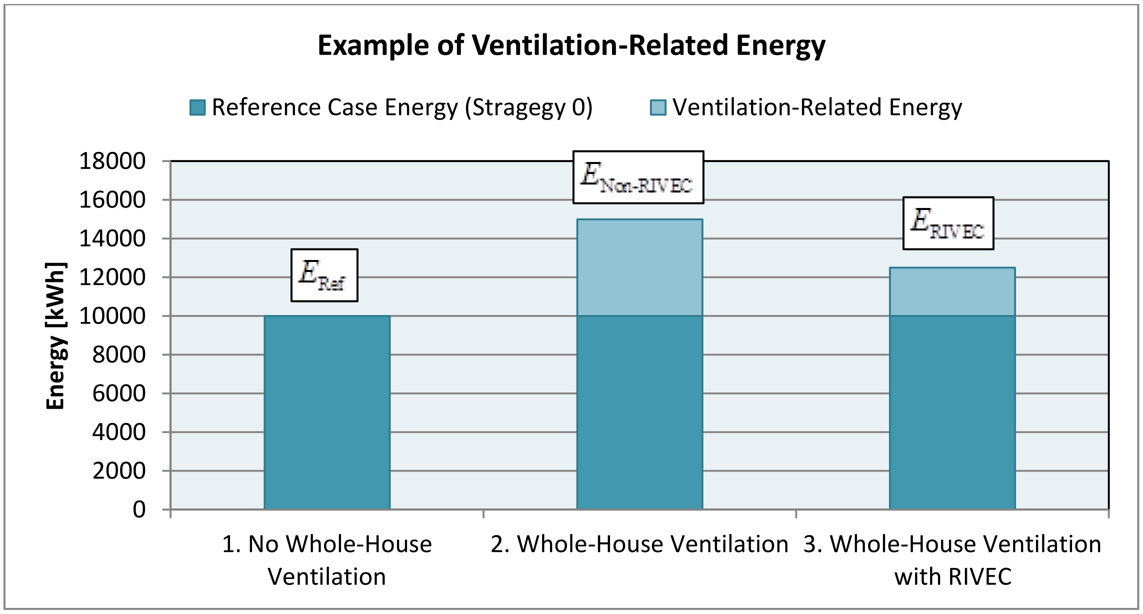


Figure 11: The ventilation-related energy is the additional energy used by the house after whole-house ventilation has been added.

For all cases the RIVEC controller saves energy by reducing the ventilation rate of the home while maintaining IAQ equivalent to or better than ASHRAE 62.2 (see Table 14 to Table 17). The amount of ventilation-related energy saved depends on the ventilation strategy, house size and climate zone. Most of the space conditioning is heating, so the colder climates see the larger absolute energy savings. Nearly all peak period ventilation-related loads were removed due to RIVEC preventing the whole-house ventilation system from running continuously during these times.

Due to the large number of simulations performed the results are displayed here in tabular form. For more detailed graphs of energy use see Appendix A. Gas used by the furnace has been converted into kWh to allow comparison with the electricity used by the air conditioning compressor, air handler and the mechanical fans.

Strategy1: Whole-House Exhaust

In the simulations, using RIVEC to control a whole-house exhaust fan reduced the annual ventilation-related energy between 38% and 52%. The mean ventilation-related energy reduction was 46%. This translates to a mean annual energy saving of 592 kWh.

Strategy 2: HRV

Heat Recovery Ventilators show lower ventilation-related energy reductions from RIVEC. The range is 25% to 38% with a mean of 31% or 876 kWh. The ventilation-related energy reductions are smaller because of the higher fan power of the HRVs compared to whole-house exhaust fans. HRVs also have built-in energy savings from the heat exchanger so there is less potential to reduce the ventilation-related energy by reducing the ventilation rate. In the warmer California climate zones such as El Centro (CZ 15) the HRV uses significantly more energy than the whole-house exhaust - approximately 5.5 times more for the Prototype C house. This is due to the small indoor-outdoor temperature differences (and therefore, limited potential for heat recovery) and the additional fan energy from operating the central air handler. HRVs are more suitable for use in the cooler climate zones such as Arcata (CZ 01).

Strategy 3: CFIS with Whole-House Exhaust

Using RIVEC to control a whole-house fan used in conjunction with a Central Fan Integrated Supply system reduced ventilation-related energy by 34% to 52%, with a mean of 43% or 573 kWh. Ventilation-related energy use is generally comparable to the whole-house exhaust system and is fairly independent of climate zone.

Strategy 4: Economizer with Whole-House Exhaust

Economizer ventilation-energy reductions ranged between 29% and 1442%. For the large house in climate zones 2 (Santa Rosa), 5 (Santa Maria), 10 (Riverside) and 15 (El Centro) the economizer cooling contribution actually reduced the total house energy use below that of the reference case. This leads to ventilation-related energy reduction figures in the order of 1000% for some cases. It should be noted that this is an artifact of the economizer and not of RIVEC. However, the absolute energy reductions are small e.g. 731 kWh or 3.6% of the space conditioning energy for the year. With these cases disregarded, operating the economizer with a RIVEC-controlled whole-house exhaust gives a mean ventilation-related energy reduction of 53% or 601 kWh. To prevent the ventilation-related energy reductions from exceeding 100%, additional simulations were performed with a new reference case for the economizer – a reference case that included economizer operation (see below).

Table 14: Reduction in ventilation-related energy from using RIVEC for Strategy 1 (Whole-House Exhaust) for different climate zones

House	***Leakage***	**1. Whole-House Exhaust Ventilation. Reduction in Ventilation-Related Energy [%]**															
	***ACH$_{50}$* [/h]**	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	45	47	47	47	44	49	48	51	50	52	49	50	51	50	54	47
	5.2	45	47	47	47	44	49	48	51	49	51	50	50	50	51	55	47
	8.6	47	48	47	48	46	51	48	51	52	53	49	50	50	51	55	47
	Mean [kWh]	920	666	585	494	643	294	354	329	354	411	580	542	523	590	376	899
Prototype C	4.8	45	48	46	47	42	48	46	49	52	51	47	50	51	48	54	45
	5.2	45	46	46	46	42	46	46	49	52	50	47	50	50	49	54	45
	8.6	45	47	45	46	42	46	46	49	50	51	48	51	50	49	54	46
	Mean [kWh]	1042	760	654	557	701	335	403	382	421	475	650	638	630	684	474	1036
Prototype D	4.8	40	42	39	42	38	39	39	44	44	44	43	44	45	43	44	41
	5.2	41	41	39	42	40	41	39	44	44	44	42	43	44	43	47	40
	8.6	39	39	41	40	36	42	38	41	46	42	43	45	44	42	49	40
	Mean [kWh]	1048	790	626	557	714	317	373	386	431	470	666	653	635	716	536	1079
All Houses	**Mean [kWh]**	1003	738	621	536	686	316	377	366	402	452	632	611	596	663	462	1005

Table 15: Reduction in ventilation-related energy from using RIVEC for Strategy 2 (HRV) for different climate zones

House	***Leakage***	**2. HRV. Reduction in Ventilation-Related Energy [%]**															
	***ACH_{50}* [/h]**	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	29	31	29	32	26	32	32	30	31	30	28	32	27	29	29	28
	5.2	31	31	29	32	25	32	31	30	31	29	28	32	27	29	29	29
	8.6	29	31	30	32	26	33	31	30	31	29	28	31	27	30	28	28
	Mean [kWh]	410	502	385	413	357	466	469	616	561	615	581	605	643	540	885	484
Prototype C	4.8	34	33	35	37	30	38	36	36	37	34	30	36	31	36	34	33
	5.2	35	33	34	37	31	38	36	36	36	34	31	35	31	36	34	33
	8.6	35	31	33	37	29	38	36	36	35	34	31	35	31	35	34	33
	Mean [kWh]	810	888	771	824	710	947	950	1322	1167	1277	1146	1194	1300	1132	1860	955
Prototype D	4.8	32	29	29	32	26	33	30	30	29	30	25	30	29	27	30	27
	5.2	32	28	29	33	25	33	30	29	29	29	25	30	29	27	30	26
	8.6	33	28	30	34	26	34	31	29	30	30	26	31	30	27	30	29
	Mean [kWh]	713	808	691	806	625	954	929	1260	1093	1296	1020	1127	1367	949	1965	681
All Houses	**Mean [kWh]**	644	733	616	681	564	789	783	1066	940	1063	915	976	1103	874	1570	707

Table 16: Reduction in ventilation-related energy from using RIVEC for Strategy 3 (CFIS) for different climate zones

House	***Leakage***	**3. CFIS with Whole-House Exhaust. Reduction in Ventilation-Related Energy [%]**															
	***ACH_{50}* [/h]**	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	42	44	44	43	41	46	44	46	46	46	44	46	46	47	51	43
	5.2	43	44	44	43	41	47	44	47	45	46	44	46	46	48	52	44
	8.6	44	46	44	44	42	48	45	47	47	47	44	45	47	47	52	44
	Mean [kWh]	882	645	560	471	616	286	335	308	336	380	547	515	497	570	366	860
Prototype C	4.8	42	45	43	43	40	45	43	45	49	46	44	45	47	46	50	44
	5.2	42	45	43	42	41	44	43	46	48	45	43	45	47	46	51	43
	8.6	43	44	42	44	41	45	43	46	46	46	44	47	45	45	49	43
	Mean [kWh]	1017	743	636	543	698	330	385	363	404	455	638	613	585	668	463	1007
Prototype D	4.8	39	40	38	38	36	37	37	41	40	39	39	41	43	42	48	39
	5.2	39	42	39	39	37	37	36	41	39	40	39	39	42	41	46	39
	8.6	37	37	37	38	34	39	36	37	40	37	40	41	41	38	46	38
	Mean [kWh]	1037	791	615	543	692	303	368	371	403	444	661	631	618	709	525	1052
All Houses	**Mean [kWh]**	978	726	604	519	669	306	362	347	381	427	615	587	567	649	451	973

Table 17: Reduction in ventilation-related energy from using RIVEC for Strategy 4 (Economizer) for different climate zones

House	*Leakage*	**4. Economizer with Whole-House Exhaust. Reduction in Ventilation-Related Energy [%]**															
	ACH$_{50}$ **[/h]**	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	45	51	43	44	51	37	45	58	60	81	62	64	63	63	69	45
	5.2	46	51	43	44	51	36	44	59	61	81	62	64	65	65	69	45
	8.6	48	53	46	46	53	36	44	57	62	85	63	62	61	61	68	45
	Mean [kWh]	927	657	570	505	611	320	369	358	393	409	615	575	573	642	395	933
Prototype C	4.8	45	50	42	41	49	30	42	52	60	76	61	65	64	60	65	42
	5.2	45	50	42	40	49	29	43	51	55	76	59	66	63	61	67	41
	8.6	46	53	42	41	53	30	41	51	55	79	61	63	62	57	61	42
	Mean [kWh]	1051	726	654	573	676	348	435	414	450	505	686	655	662	734	509	1072
Prototype D	4.8	42	137	46	57	1041	34	47	52	77	426	55	48	49	64	123	38
	5.2	43	146	47	55	499	34	49	45	78	1149	55	53	50	66	134	38
	8.6	42	287	50	61	133	34	55	59	95	1442	58	56	47	62	164	38
	Mean [kWh]	1041	724	621	525	625	348	368	344	394	461	655	608	684	761	521	1100
All Houses	**Mean [kWh]**	1006	702	615	535	637	339	391	372	412	459	652	613	640	712	475	1035

Strategies 1 to 4

On average across all climate zones, house sizes and envelope leakages, Figure 12 shows that the RIVEC controller reduced the ventilation-related energy by 46% for Strategy 1 (whole-house), 31% for Strategy 2 (HRV), 43% for Strategy 3 (CFIS) and 53% for Strategy 4 (Economizer minus the climate zones 2, 5, 10 and 15 - see above). This is an average of 43% across all mechanical ventilation strategies. The changes in ventilation-related energy reductions had greater climate variability than the fractional savings but small variability between house sizes and envelope leakage levels. The following results for climate variability are averaged over all house sizes and envelope leakages. For the Exhaust, CFIS and Economizer systems the ventilation-related energy reductions were similar, ranging from a little over 300 kWh/year in climate zone 6 to about a 1000 kWh/year in Climate Zones 1 & 16. For the HRV, it acts to reduce the energy penalty in colder climates (climate zones 1 and 16) with the result that the smallest reductions in ventilation-related energy are about 600 kWh/year in climate zone 3 and the greatest reductions are 1600 kWh/year in climate zone 15.

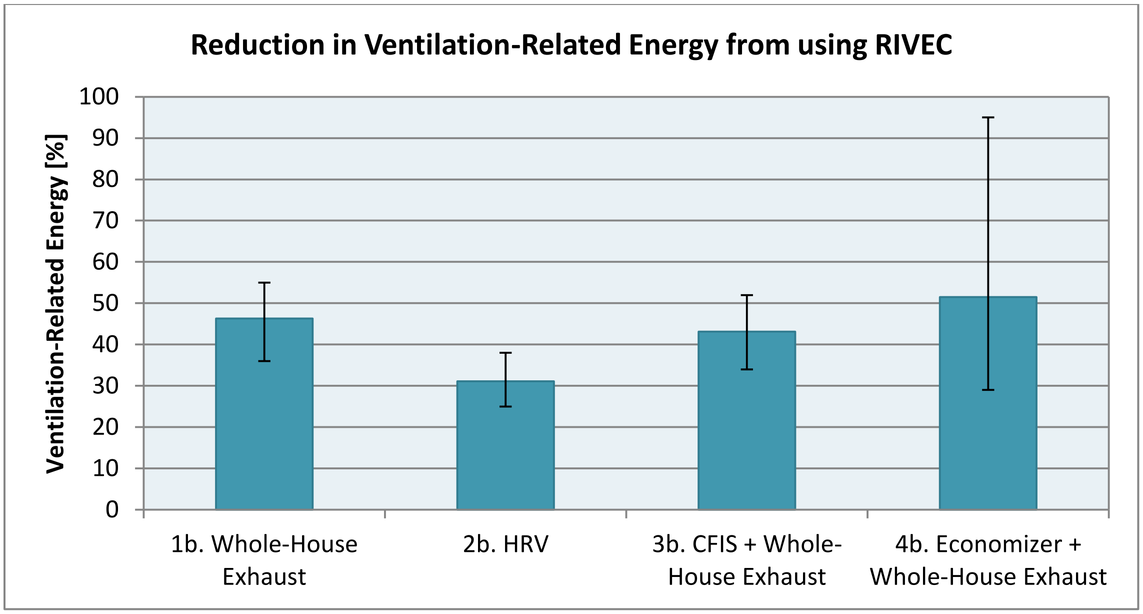


Figure 12: The reduction in ventilation-related energy from using RIVEC averaged across all house sizes, envelope leakages and climate zones

For California these ventilation-related energy reductions can be translated into savings across the state if RIVEC strategies are implemented. Walker and Sherman (2006a) have shown that residential ventilation systems compliant with the expected new California standards would represent between 5% to 32% of the total building load in California, depending on the system chosen. According to the simulations in this report, RIVEC can reduce this portion of the total building load by at least 25%. Under the (albeit crude) assumption that the four whole-house mechanical ventilation strategies are equally prevalent in California we obtain an average ventilation-related energy reduction across all simulated house sizes, envelope leakage and ventilation strategies, of 43%. To estimate potential electricity savings the 84,000 GWh used for residential heating and cooling (CEC, 2011) is multiplied by the fraction of total building load that is due to infiltration (approximately one third) to obtain the ventilation load of 28,000 GWh. Only about one quarter of the CA building stock will be tight enough to need mechanical ventilation so the total potential energy to be reduced by RIVEC is 7,000 GWh. On average, RIVEC reduces this energy by 43% or 3,010 GWh.

Envelope Leakage & House Size Dependency for RIVEC Controlled Systems

The results for ventilation strategies 1 to 4 show little dependence on house envelope leakage when considering the reduction in ventilation-related energy from using RIVEC (Table 14 to Table 17). For whole-house mechanical ventilation (Strategy 1) the mean difference between the reductions in ventilation-related energy from RIVEC for the three envelope leakages is 1.38% with a maximum difference of 5%. For the HRV simulations (Strategy 2) the mean difference is 0.83% with a maximum difference of 3%. For the CFIS (Strategy 3) simulations the mean difference is 1.56% and maximum difference is 5%. The economizer (Strategy 4) is slightly different. Again, disregarding the simulations for the large house where the economizer cooling contribution actually reduces the total house energy use below that of the reference case (climate zones 2 , 5, 10 and 15), the mean difference between ventilation-related energy saved by RIVEC for the three envelope leakages is 3.23% with a maximum difference of 18%. These results show that RIVEC ventilation-related energy reductions are robust over a wide range of envelope leakage.

The general trend when observing the effect of house size on the ability of RIVEC to reduce the ventilation-related energy, is that larger homes have slightly lower fractional reductions for strategies 1-3 (4.5 percentage points lower on average, or about 10% of the ventilation-related energy reduction). There is no such trend for the economizer results with some climate zones showing an increase in ventilation-related energy with house size, and other climate zones showing a decrease. Some of this variability is due to the geometry of the three buildings not simply scaling with floor area. Prototype B and C are both single story buildings and Prototype D is a two story building with a different shape. The size of the garage for Prototypes B and C was the same, so the ratio of the different wall lengths was not the same for both houses. The different ratio means that the wind-driven flows won't scale the same between the different houses.

Economizer Operation Times

Figure 13 and Figure 14 show the times of the year during which the economizer operates, plotted with the mean outdoor air temperature. Results are for the Prototype C house with medium envelope leakage (5.2 ACH_{50}). The mild climate zones (e.g. L.A. – 1,034 hours, and Burbank – 1,073 hours) see the most hours of operation, especially during the summer months when indoor temperatures are high enough. In the hotter climates (e.g. China Lake, and El Centro) it is too hot at night for economizer operation during the summertime and it only operates during the shoulder seasons. The coldest climate (Arcata) sees very little economizer operation due to low outdoor temperatures.

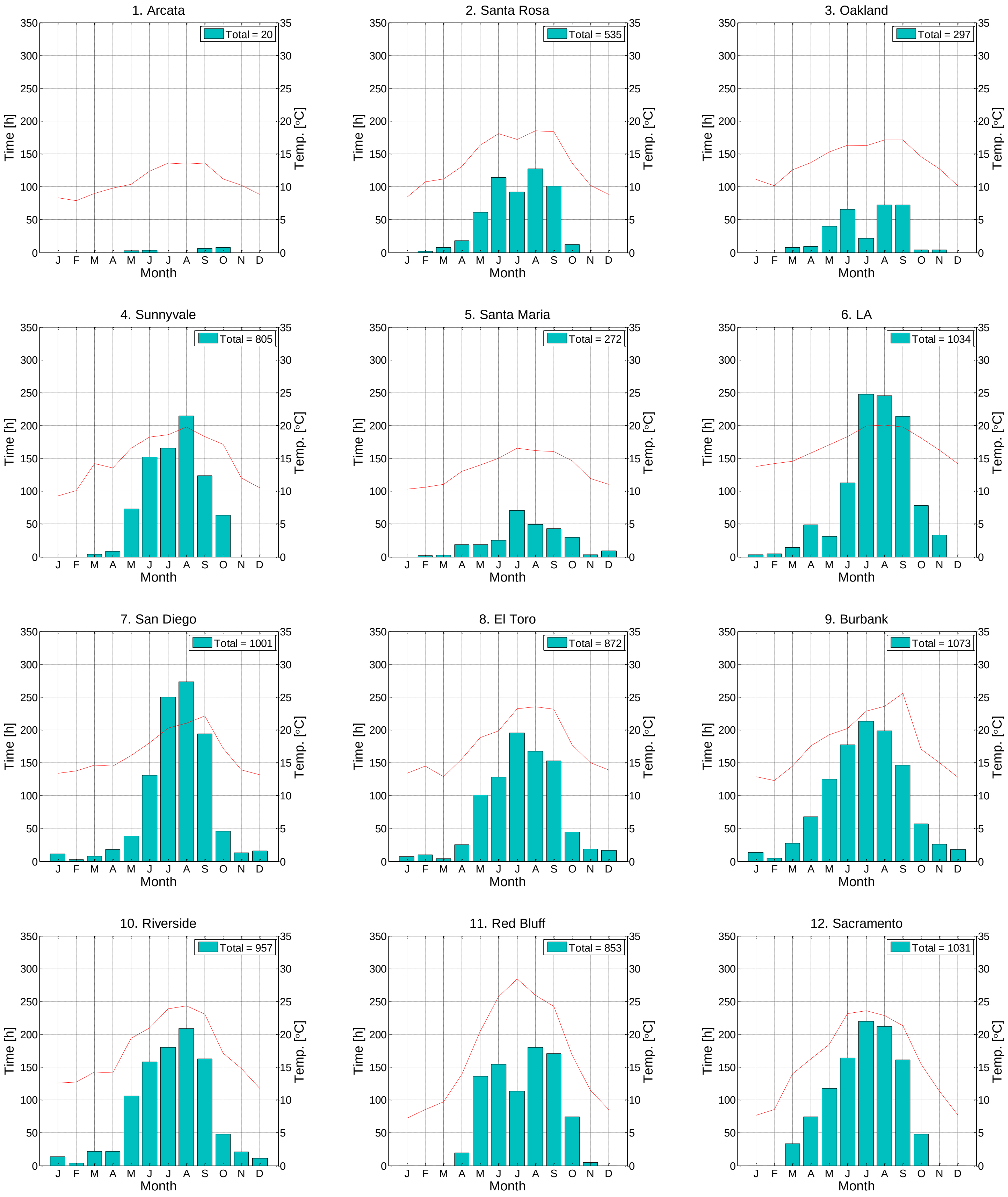


Figure 13: Hours of operation for the economizer, and mean outdoor temperature (red line) by month. Prototype C house with medium envelope leakage (Climate zones 1 to 12)

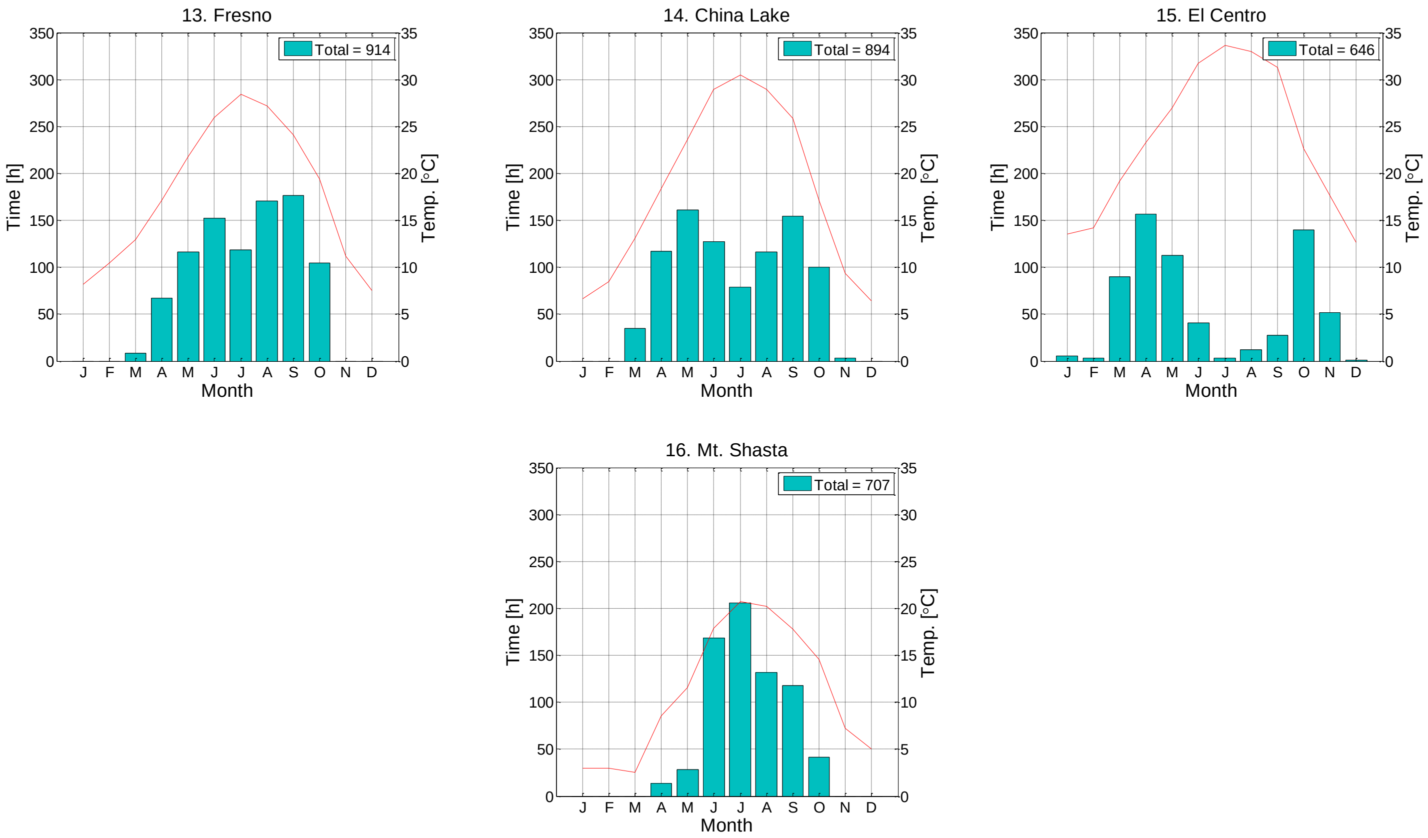


Figure 14: Hours of operation for the economizer, and mean outdoor temperature (red line) by month. Prototype C house with medium envelope leakage (Climate zones 13 to 16)

Economizer – Alternative Reference Case

Economizers are primarily meant as cooling devices. Because they use large amounts of outside air to cool the building mass, they also ventilate incidentally. If the economizer should not be considered as part of the ventilation system, a new reference case needs to be defined for the economizer simulations. The new reference case includes the economizer operation i.e. the new reference is a house that *does not* have a whole-house ventilation system (as before) but *does* have an economizer. This could be applicable to retrofit situations where an economizer is already present in a house before the installation of RIVEC.

Table 18 shows the change in ventilation-related energy from using RIVEC when using the alternative reference case for the economizer simulations. RIVEC reduces the ventilation-related energy by 37% to 63% with a mean value of 52% across all house sizes, envelope leakages and climate zones. The absolute energy savings in kWh are the same as before, as the new reference case just subtracts a different constant from the total energy use – the energy differences between the RIVEC and non-RIVEC cases remains the same.

Table 18: Reduction in ventilation-related energy from using RIVEC for Strategy 4 (Economizer) for different climate zones

House	***Leakage*** **ACH_{50} [/h]**	**Economizer – Alternative Reference. Reduction in Ventilation-Related Energy [%]**															
		1	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	47	52	50	51	49	61	54	59	58	57	54	55	56	55	60	49
	5.2	48	52	50	50	49	61	53	59	59	56	55	55	58	56	60	49
	8.6	50	52	53	55	48	62	56	59	60	60	55	54	56	56	62	50
	Mean [kWh]	927	657	570	505	611	320	369	358	393	409	615	575	573	642	395	933
Prototype C	4.8	47	51	50	52	46	56	56	58	59	60	53	54	56	53	60	47
	5.2	47	51	50	52	45	56	56	57	55	59	52	55	55	55	62	47
	8.6	48	51	49	53	49	58	53	59	60	58	53	53	56	53	60	48
	Mean [kWh]	1051	726	654	573	676	348	435	414	450	505	686	655	662	734	509	1072
Prototype D	4.8	42	45	43	47	42	52	45	44	51	58	45	44	50	48	59	43
	5.2	42	44	44	44	43	52	46	40	50	48	45	49	52	49	63	42
	8.6	42	44	44	44	37	53	47	53	50	51	46	46	50	43	51	43
	Mean [kWh]	1041	724	621	525	625	348	368	344	394	461	655	608	684	761	521	1100
All Houses	**Mean [kWh]**	1006	702	615	535	637	339	391	372	412	459	652	613	640	712	475	1035

Passive Stack Sizing and Performance

The effectiveness of passive stacks depends on the air leakage of the building. Leakier buildings offer less airflow resistance and promote ventilation through the passive stack. Ideally the passive stack would be sized based on the overall tightness of the building envelope as well as the conditioned floor area. However, to simplify the analysis and discussion, only the medium leakage (5.2 ACH_{50}) houses will be considered.

Passive Stack Sizes

Cross-sectional areas for the passive stacks were determined for the three prototype houses with the medium envelope leakage (5.2 ACH_{50}). Several combinations of passive stacks (Table 19) were used so that ventilation rates through the passive stacks met or exceeded ASHRAE 62.2 for at least 80% of the year).

Table 19: Passive stack diameters and cross-sectional areas

Passive Stack Diameter [cm]	Total Stack Cross-Sectional Area				
	[mm^2]	[cm^2]	[m^2]	[in^2]	[ft^2]
1 x 15	70,700	707	0.07	110	0.8
1 x 20	125,700	1257	0.13	195	1.4
1 x 15 and 1 x 20	196,300	1963	0.20	304	2.1
2 x 20	251,300	2513	0.25	390	2.7
1 x 15 and 2 x 20	322,000	3220	0.32	499	3.5
3 x 20	377,100	3771	0.39	585	4.2

Table 20 shows the cross-sectional areas and Table 21 shows the time of the year that the stacks meet ASHRAE 62.2. Simulated passive stacks had diameters of 15 and 20 cm. It is important here to distinguish between the stack airflow rate and the house airflow rate. The house airflow rate includes infiltration, auxiliary (source control) exhaust fans and the passive stack. The stack airflow rate only refers to the air flowing through the passive stack, and is discussed here to allow comparison with the four simulated mechanical ventilation systems from a standards perspective (with the assumed infiltration credit), i.e. to show how passive stack flows compare to ASHRAE 62.2.

Table 20: Passive stack cross-sectional areas for the prototype houses. Up to three stacks with combinations of diameters of 15 and 20 cm were used.

	Passive Stack Total Cross-Sectional Area [m^2]															
CZ	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Pro B	0.13	0.20	0.13	0.13	0.13	0.13	0.20	0.25	0.25	0.20	0.20	0.20	0.20	0.20	0.39	0.13
Pro C	0.13	0.13	0.13	0.13	0.13	0.13	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.32	0.13
Pro D	0.13	0.20	0.13	0.20	0.13	0.20	0.20	0.25	0.25	0.20	0.20	0.20	0.20	0.20	0.39	0.13

Table 21: Time of year airflow through passive stack meets ASHRAE 62.2 minimum [percent of year]

	Percent of Year [%]															
CZ	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Pro B	89	87	89	83	87	85	87	85	85	84	82	85	81	82	80	83
Pro C	93	81	93	84	90	86	92	82	84	87	85	86	83	83	83	84
Pro D	88	89	88	91	84	94	91	84	85	85	83	84	81	81	82	74

Smaller stack sizes are required for the cold climate zones with large indoor-outdoor temperature differences, and for the windy climate zones. Each of the prototype houses in Climate zone 3 (Oakland) only requires a 0.13 m^2 stack because of the cool winters and cool summer nighttime temperatures, and the (comparatively) high wind speeds. Climate zone 15 (El Centro) is characterized by extremely hot and dry summers and very short winters. In this climate zone a combination of three 0.13 m^2 passive stacks was required to meet ASHRAE 62.2 for 80% of the year for prototypes B and D.

It is interesting to note that for some climate zones (e.g. Climate Zone 2 - Santa Rosa) the smaller Prototype B house requires a larger passive stack than the larger Prototype C house. This is due to a combination of three things. Firstly, the smaller house has a smaller envelope leakage area and hence a larger resistance to airflow. Natural ventilation is most effective when the resistance to airflow is low. Secondly, the Prototype B house has a much smaller floor area than the Prototype C house, yet they both have the same number of occupants (four). This affects the calculation of $Q_{62.2}$in Equation (1) so that the minimum airflow rate required, when expressed in air changes per hour, is less for the Prototype B house than the Prototype C house. Thirdly, the default infiltration credit of 10 L/s per 100 m^2 is dependent on floor area only and acts as a baseline to meet the $Q_{62.2}$ target in our calculations. So the baseline is higher (19.5 L/s) for the prototype C house than for the prototype B house (11.1 L/s). The combination of these three factors means that the same sized stack can meet ASHRAE 62.2 for 80% of the year in the medium sized house but not the smaller house in certain climate zones. It should be noted that the default infiltration credit was included in the passive stack calculations to maintain consistency and allow direct comparison with the mechanical ventilation simulations.

The passive stacks sized to meet ASHRAE 62.2 for 80% of year were oversized and flow limited to 125% of the ASHRAE 62.2 minimum airflow rate. If the original passive stack satisfied ASHRAE 62.2 for 85% or more of the year then it was simply flow limited. Otherwise, the passive stack was increased to the next size up allowed by the 15 and 20 cm diameter configurations (Table 22). For example, a 20 cm stack would be increased to a 20 cm stack and a 15 cm stack; two 20 cm stacks would be increased to two 20 cm stacks and one 15 cm stack etc.

As before with the non-flow limited passive stack, the percentage of the year that airflow through the flow limited passive stack meets ASHRAE Standard 62.2 is shown (Table 23).

Table 22: Oversized and flow Limited passive stack cross-sectional areas for the prototype houses. Up to three stacks with combinations of diameters of 15 and 20 cm were used.

	Flow Limited Passive Stack Cross-Sectional Area [m^2]															
CZ	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Pro B	0.13	0.20	0.13	0.20	0.13	0.13	0.20	0.25	0.25	0.25	0.25	0.20	0.25	0.25	0.39	0.20
Pro C	0.13	0.20	0.13	0.20	0.13	0.13	0.20	0.25	0.25	0.20	0.20	0.20	0.25	0.25	0.39	0.20
Pro D	0.13	0.20	0.13	0.20	0.20	0.20	0.20	0.32	0.25	0.20	0.25	0.25	0.25	0.25	0.39	0.20

Table 23: Time of year airflow through flow oversized and flow limited passive stack meets ASHRAE 62.2 minimum [percent of year]

	Percent of Year [%]															
CZ	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Pro B	89	87	89	90	87	85	87	85	85	89	86	85	84	85	74	90
Pro C	93	90	93	93	90	92	87	87	87	85	85	86	87	86	80	93
Pro D	88	89	88	91	96	94	91	86	85	85	87	88	85	85	81	95

Passive Stack and Hybrid IAQ

To show compliance with ASHRAE Standard 62.2 the hourly relative dose and exposure was tracked during occupied times and then averaged over the year. Figure 15 shows a summary of the occupied dose for ventilation strategies 1, 5a, 5b and 6. Figure 16a and b to Figure 20a and b show the hourly mean, minimum and maximum dose and exposures by climate zone, for the Prototype C house with medium envelope leakage (for strategies 0, 1a, 5a, 5b, and 6). This time the dose and exposure was calculated using the total house airflow rate - not just the sum of the mechanical airflow rates plus the default infiltration credit (as was used in the mechanical ventilation cases). This was because the passive stacks interact with the infiltration airflow in and out of the building envelope, so the total house airflow rate is more appropriate in this case. This is termed the 'real' occupied dose and exposure.

It is important to ensure that acute exposure levels are not exceeded too often or for too long. For example, asthmatics or rhinitis sufferers sensitive to contaminants such as formaldehyde could face considerable discomfort when exposed to high pollutant levels over short time scales, even though the annual averages are below the acceptable levels. All of the one-hour maximum exposure values are below 2.5, meaning that the one-hour maximum acute-to-chronic ratio of 4.7 and the 8-hour maximum of 5.4 are not reached (from Table 1). The relative dose maximums do not exceed 1.6 so the 24-hour maximum acute-to-chronic ratio of 2.5 is also not met.

The occupied dose for the passive stack ventilation with no flow limiting (5a) is 12% lower than the mechanical exhaust (1a). This indicates over-ventilation and results from there being no control over the ventilation rate. For strategies 5b and 6 the airflow-limiting control measures mean that the dose is much closer to one.

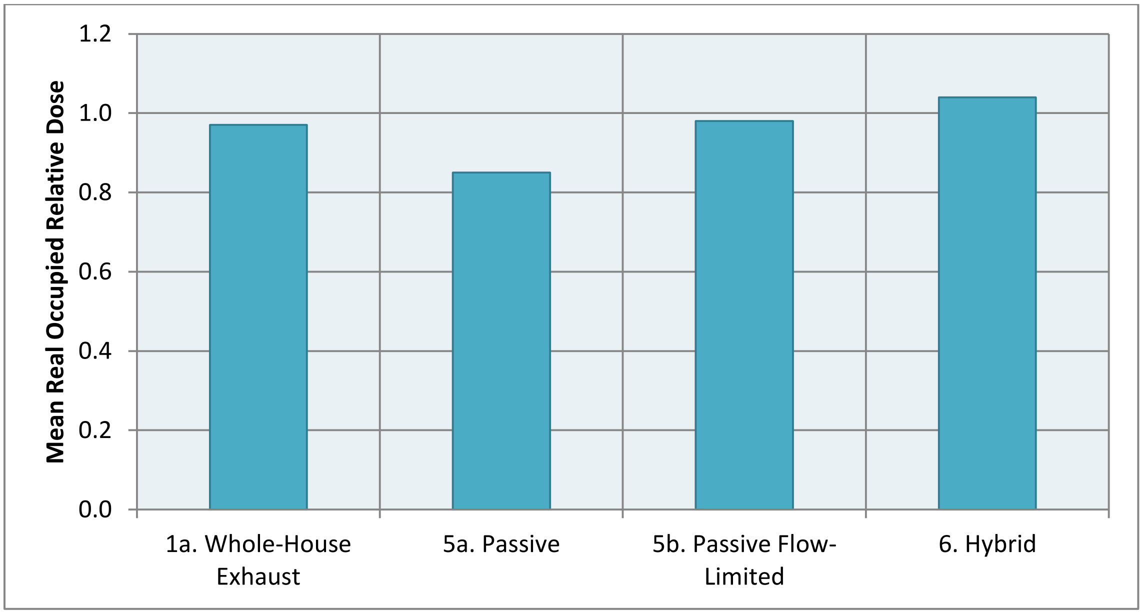


Figure 15: 'Real' occupied relative dose (hourly) averaged over all house sizes, envelope leakages and climate zones

The reference case (Strategy 0) shows high exposures and doses with annual averages for both above 1.5. Hourly maximums for exposure reach more than 3.5. Hourly maximums for dose exceed 2.5. This demonstrates a need for ventilation. Adding mechanical ventilation (Strategy 1a) brings the averages for exposure and dose down to approximately one. The minimums are restricted to 1.5 for exposure and 1.25 for dose. The passive stack ventilation (Strategy 5a) brings the annual mean exposure and dose down further, but the maximums increase because of the times of the year when the natural driving forces are low, and the ventilation rate is low. Oversizing and flow-limiting the passive stacks (Strategy 5b) reduces the maximums and increases the minimums for the exposure and dose, compared to Strategy 5a. This is a result of larger airflows from the larger stack, but reduced times of over-ventilation from the flow-limiting controls.

For the hybrid case (Strategy 6), the RIVEC controller forces the whole-house fan to be off for at least 4 hours per day during the peak period. This means that the hourly exposures are higher than for Strategy 1a. But RIVEC turns on the whole-house fan at other times to compensate, and so keeps the mean annual dose close to one.

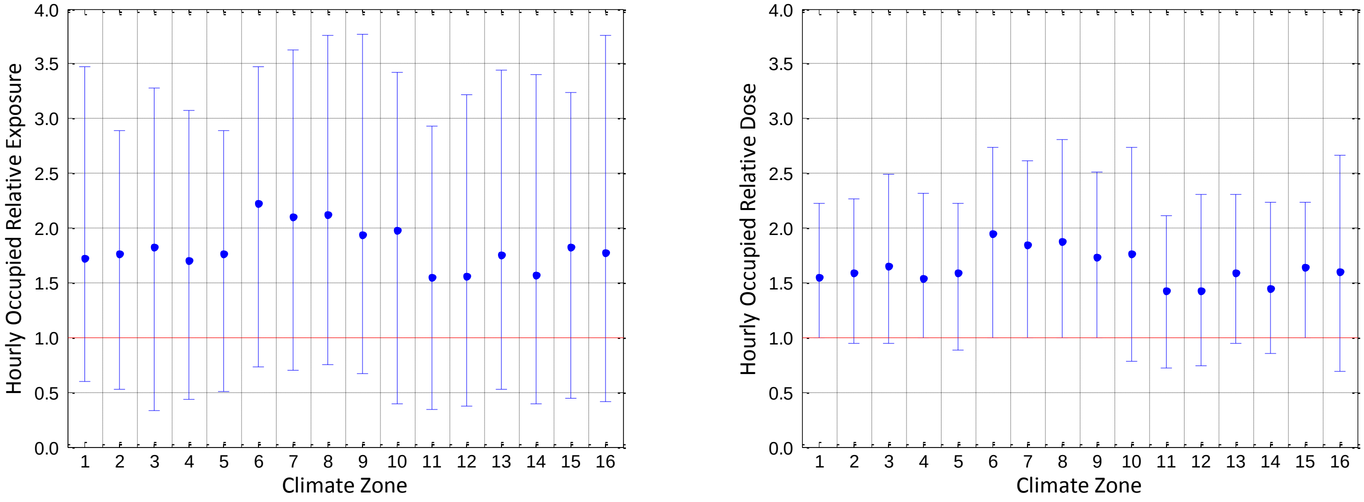


Figure 16a and b: Reference Case (0)

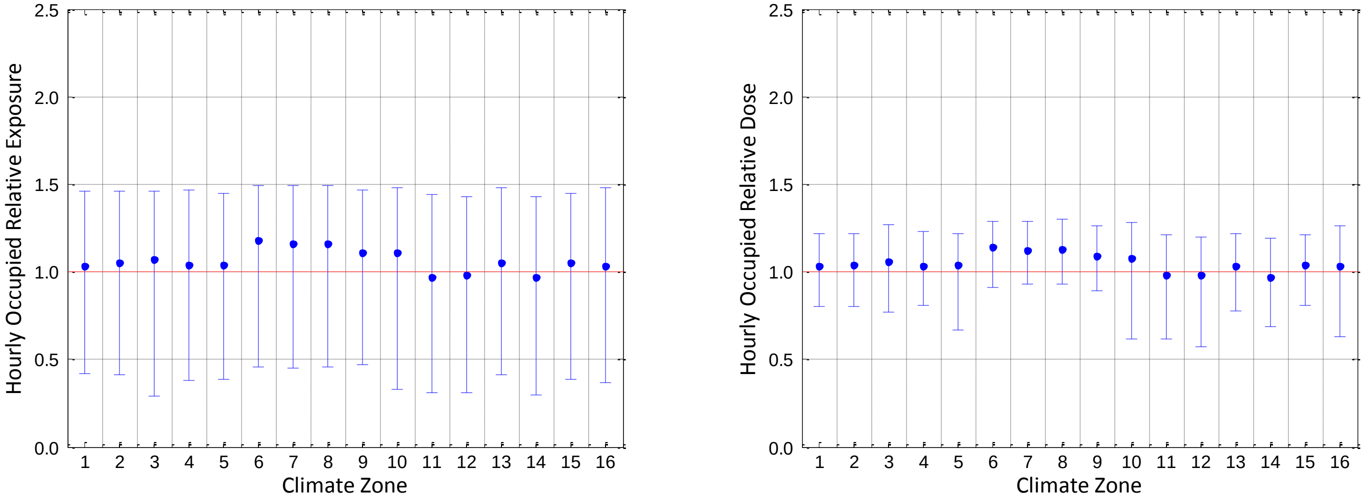


Figure 17a and b: Mechanical Whole-House Exhaust Case (1a)

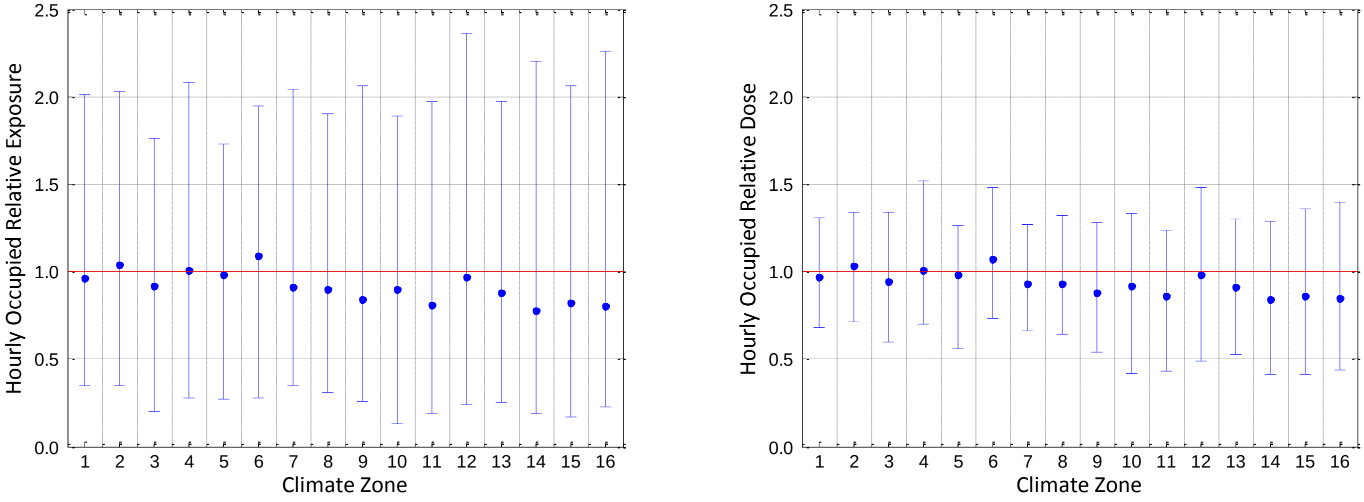


Figure 18a and b: Passive Case (5a)

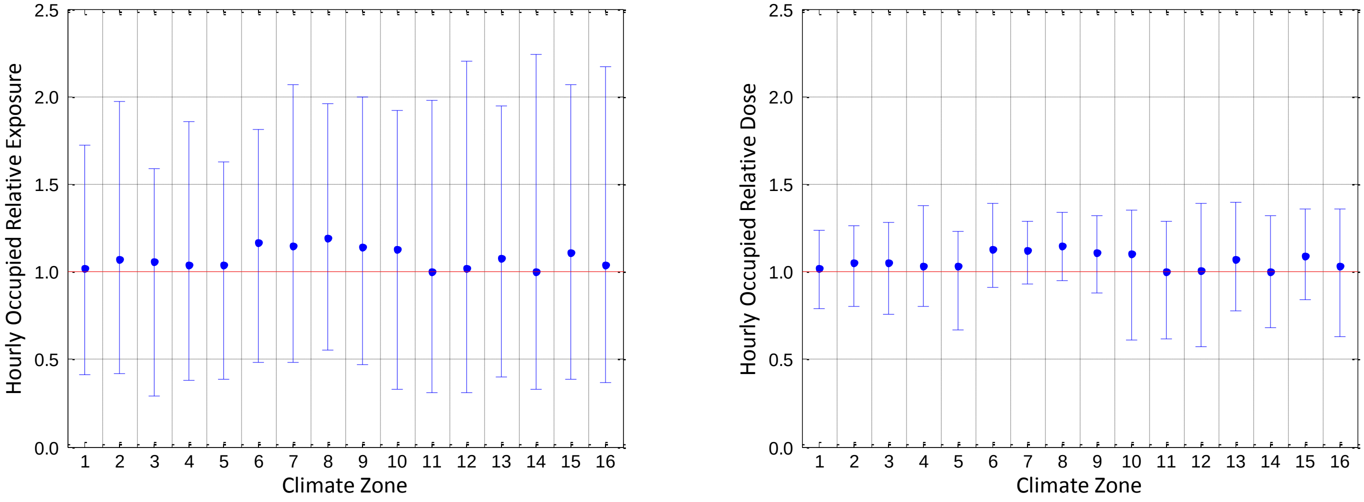


Figure 19a and b: Passive flow limited case (5b)

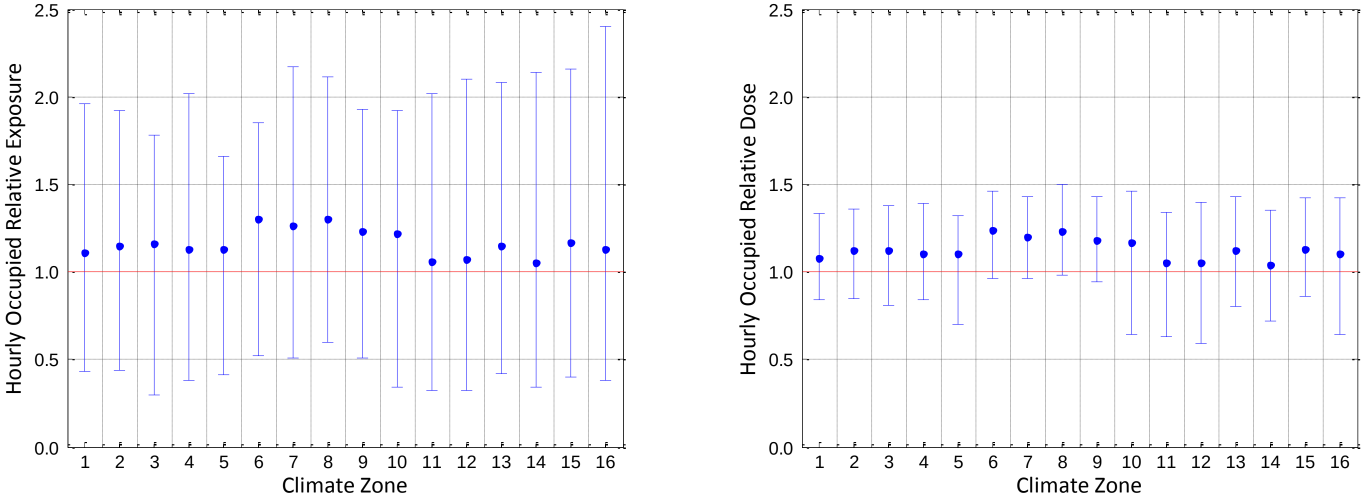


Figure 20a and b: Hybrid Case (6)

Passive and Hybrid Ventilation-Related Energy Use

Figure 21 shows the fractional ventilation-related energy for Strategy 1a (whole-house exhaust), 5a (passive stack), 5b (oversized and flow limited passive stack), and 6 (hybrid ventilation), averaged over all house sizes, envelope leakages and climate zones. The results have been normalized so that the ventilation-related energy for the Strategy 1a represents 100%. Strategy 5a, on average, uses 70% more ventilation-related energy than a standard whole-house exhaust. The lack of flow regulation for the passive stack means that the space-conditioning load can increase considerably. Strategy 5b uses approximately the same amount of ventilation-related energy as Strategy 1a. For some times of the year the flow limited passive stack will over-ventilate, and for others it will under-ventilate. Over all climate zones the over- and under-ventilation tend to balance each other out. However, the remaining difference can be attributed to the fan energy which is not required by Strategy 5b. Strategy 6 uses 20%

less ventilation-related energy than the whole-house exhaust. There is much reduced fan energy compared to Strategy 1a, and the airflow is limited to 100% of the 62.2 whole-house rate so there is no over-ventilation with a subsequent increase in space-conditioning load. The RIVEC-controlled fan is sized to 125% of the ASHRAE 62.2 minimum.

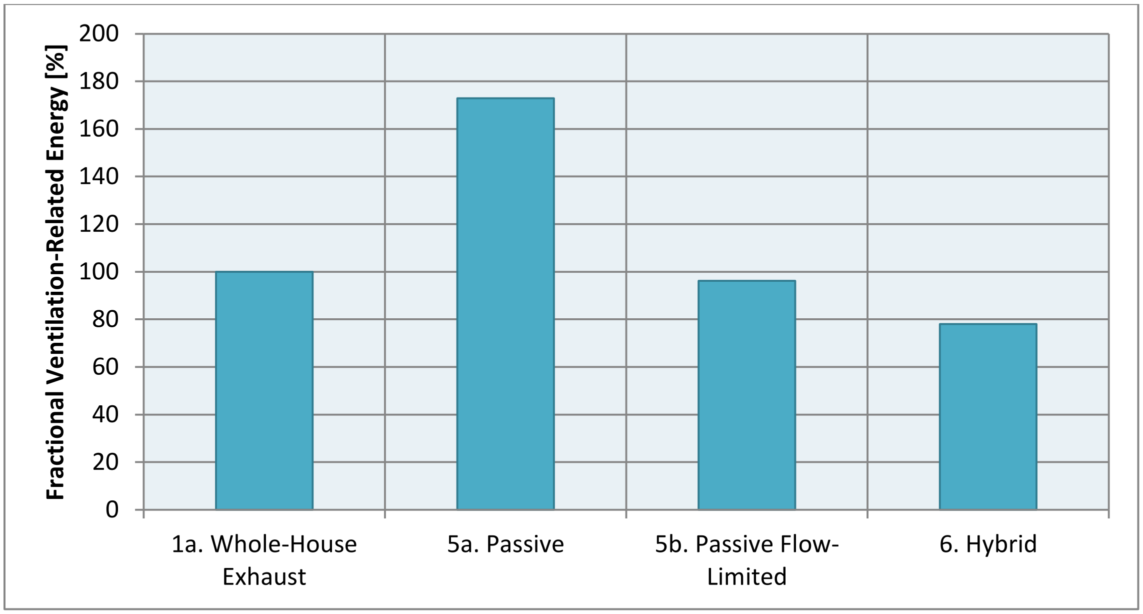


Figure 21: Fractional ventilation-related energy averaged over all house sizes, envelope leakages and climate zones

Figure 22 shows the ventilation-related energy for all climate zones and house sizes with the medium (5.2 ACH_{50}) envelope leakage. For most climates the variation in ventilation-related energy is small between the whole-house exhaust, flow-limited passive stack and hybrid strategy. Therefore, the decision to implement any of these strategies would come down to user preference, ease of installation and cost. Results for the tight and leaky houses can be found in Appendix B.

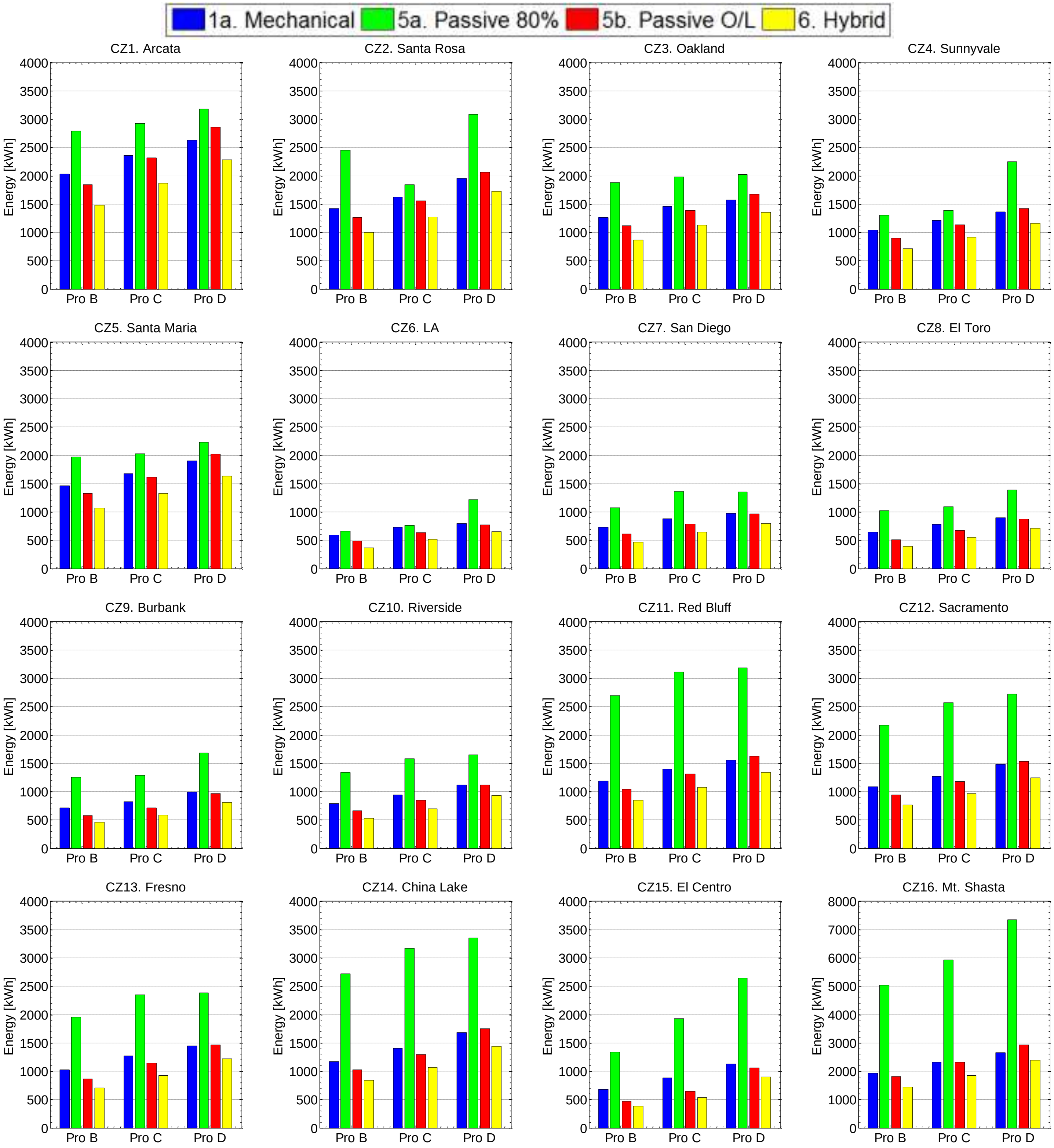


Figure 22: Ventilation-related energy incurred from adding whole-house ventilation (mechanical, passive, passive oversized and limited, and hybrid). Envelope Leakage = 5.2 ACH_{50}.

Peak Load Reduction

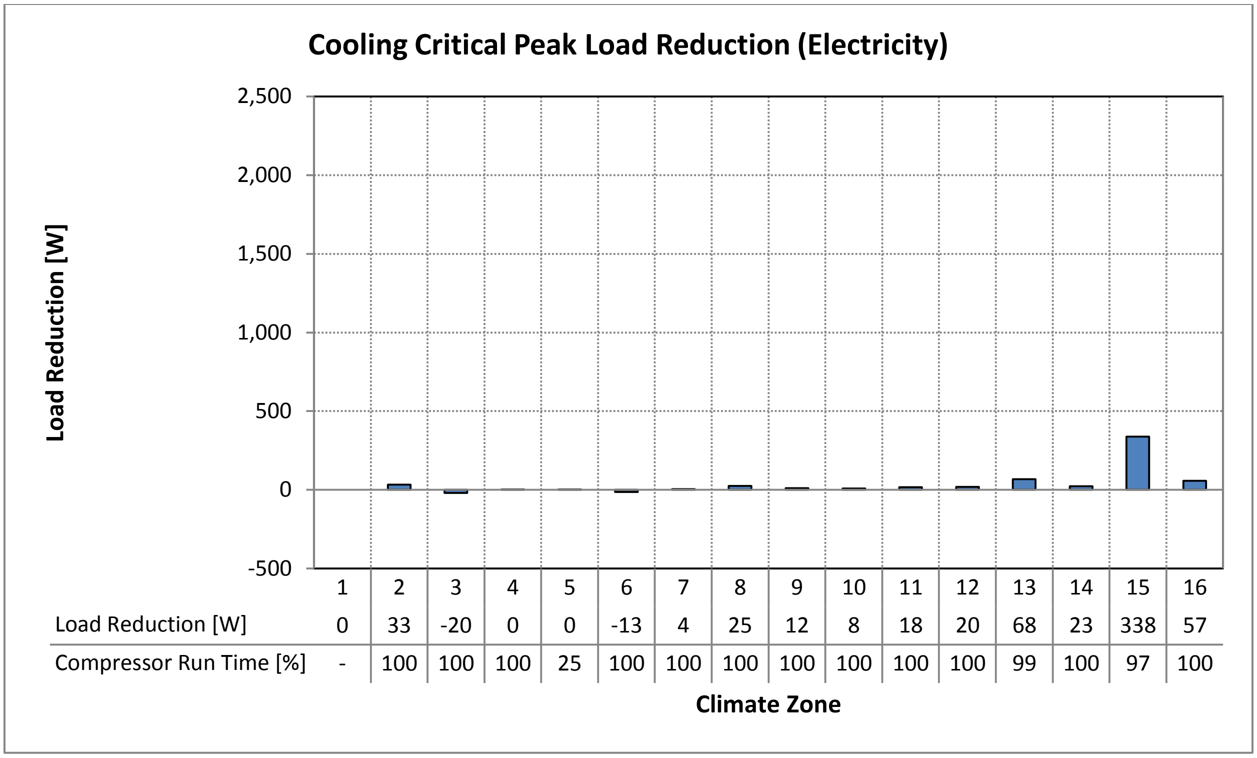
RIVEC acts as a demand response system by turning off the whole-house ventilation during peak load periods. Reducing the outside ventilation air entering the house during the hottest and coldest parts of the day should reduce the demand on the heating and cooling equipment.

Two types of load reduction are discussed in this report, the *critical* peak load reduction and the *average* peak load reduction.

Critical Peak Load Reduction

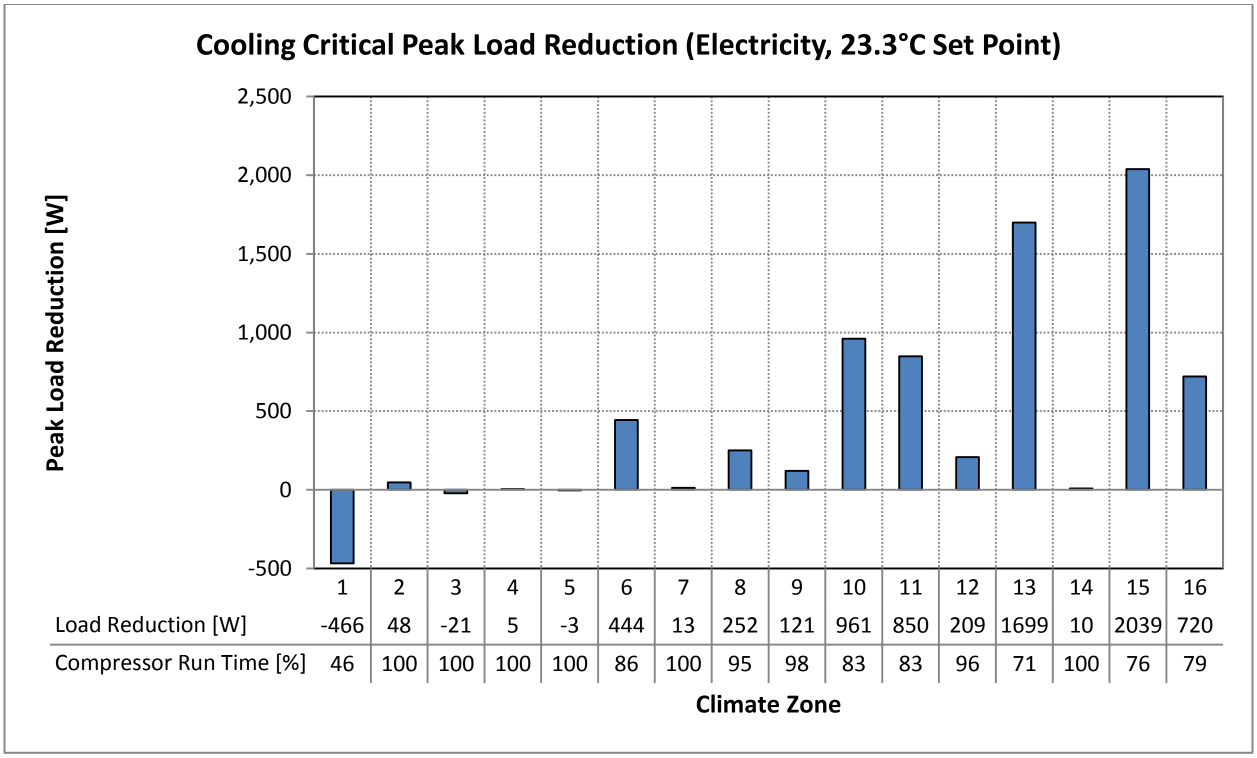
The *critical peak* represents the period in the year when the demand on the space conditioning equipment is the largest. In this work, the heating critical peak is defined as the average total building power draw for the five hours in the year with the largest heating load. The cooling critical peak is the same except for the largest cooling load. The total power used by the air handler, furnace, air conditioner and ventilation system was calculated for each hour of the year. The hourly data was sorted to find the hours of maximum heating and cooling power draw for the non-RIVEC case, which occurred during the peak times programmed into RIVEC (i.e. 2 a.m. to 6 a.m. for heating and 4 p.m. to 8 p.m. for cooling). The power draw for the corresponding hours from the RIVEC simulations was compared to the power draw for the peak hours in the non-RIVEC case. The results were averaged over the highest five power draw hours for the year to remove some of the sensitivity to selecting an individual peak hour.

Because a continuous exhaust is likely to be the most common whole-house ventilation system and because the continuous exhaust gives results that are conservative in terms of energy savings, Strategy 1 was chosen for this analysis. The critical peak period power reductions are summarized in Figure 23 to Figure 25. Gas consumption of the furnace is included in Watts for better comparison and so that it can be combined with the air handler and ventilation fan power. Furnace and compressor run times over the five critical peak hours are included in the figures. The results below are for the medium sized, Prototype C house with medium air leakage (5.2 ACH_{50}). For the other two houses see Appendix C.



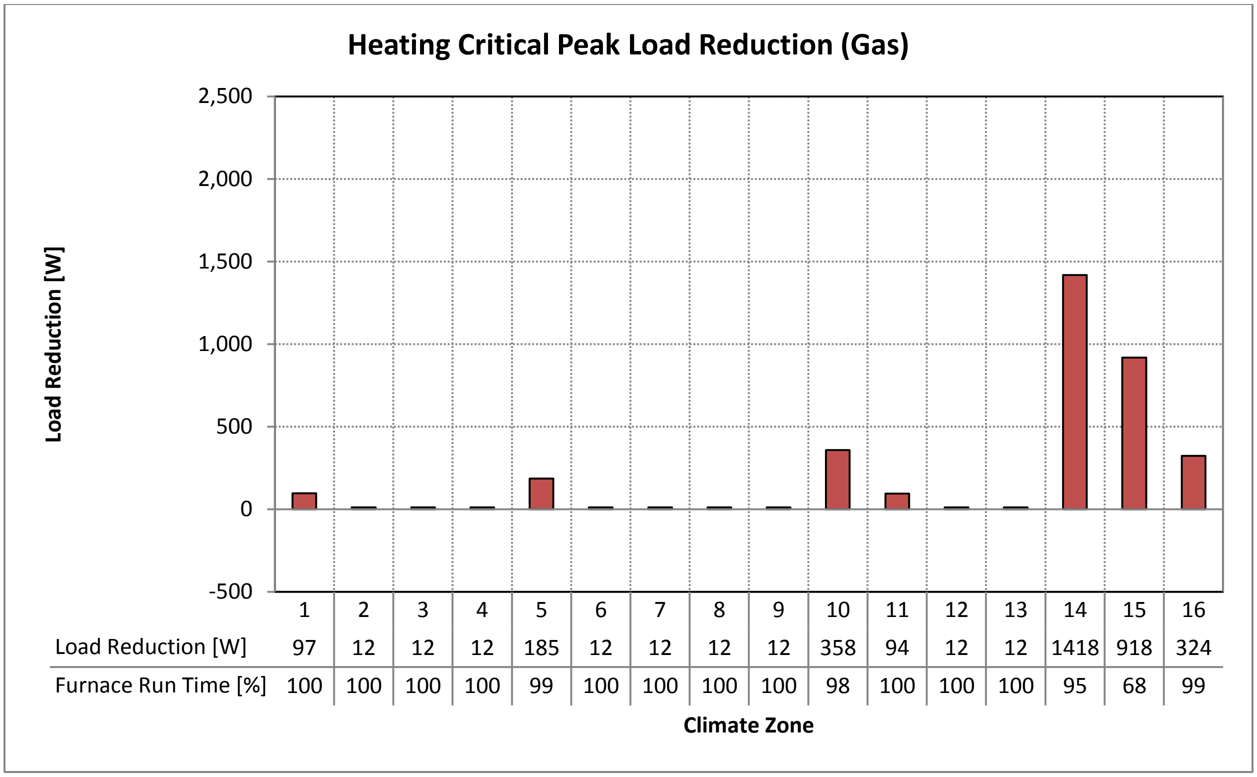
Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Load Reduction [W]	0	33	-20	0	0	-13	4	25	12	8	18	20	68	23	338	57
Compressor Run Time [%]	-	100	100	100	25	100	100	100	100	100	100	100	99	100	97	100

Figure 23: Cooling critical peak load avoided using RIVEC (whole-house exhaust, Pro C house with medium envelope leakage)



Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Load Reduction [W]	-466	48	-21	5	-3	444	13	252	121	961	850	209	1699	10	2039	720
Compressor Run Time [%]	46	100	100	100	100	86	100	95	98	83	83	96	71	100	76	79

Figure 24: Cooling critical peak load avoided using RIVEC with a 23.3°C cooling set point throughout the cooling season (whole-house exhaust, Pro C house with medium envelope leakage)



Climate Zone	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Load Reduction [W]	97	12	12	12	185	12	12	12	12	358	94	12	12	1418	918	324
Furnace Run Time [%]	100	100	100	100	99	100	100	100	100	98	100	100	100	95	68	99

Figure 25: Heating critical peak load avoided using RIVEC (whole-house exhaust, Pro C house with medium envelope leakage)

Figure 23 shows the cooling critical load reductions from using RIVEC with the Title 24 thermostat temperature set points. Savings are small because the Title 24 set points already factor in peak load avoidance by raising the cooling set points during the day. This helps prevent the air-conditioner from running. Figure 24 shows the cooling critical peak reduction when the cooling set points have been lowered to 23.3°C (74°F) for the entire cooling season. We now see much larger load reductions. The maximum is 2,039 W in the low desert climate zone 15 (El Centro). The lowest is in climate zone 1 (Arcata) where the load is increased by 466 W. However, there is only one cooling peak period in Arcata with the 23.3°C set point and RIVEC simply causes the air conditioning to turn on one hour earlier due to the prevention of ventilation cooling.

Sizing of the cooling equipment is an issue. To allow critical peak load reductions from RIVEC the equipment needs to be sized so that it may cycle. If it is not, then during the critical peak hours the compressor simply runs all of the time, whether the ventilation rate is reduced or not. An example of this is the high desert climate zone 14 (China Lake) with hot summer days. The air conditioning compressor runs for 100% of the time over the five critical hours so critical load reductions are small (10 W).

Equipment sizing is also an issue for heating. Figure 25 shows the heating critical peak period reduction. For each climate zone where the furnace fractional running time is 100% there are no critical peak savings.

Average Peak Load Reduction

The difference in load between coincident peak periods between the non-RIVEC and RIVEC results were averaged for the whole year. Figure 26 to Figure 28 show the annual average peak load reduction for electricity and for gas. Again, results are for ventilation Strategy 1 (whole-house exhaust), Prototype C home with medium air leakage.

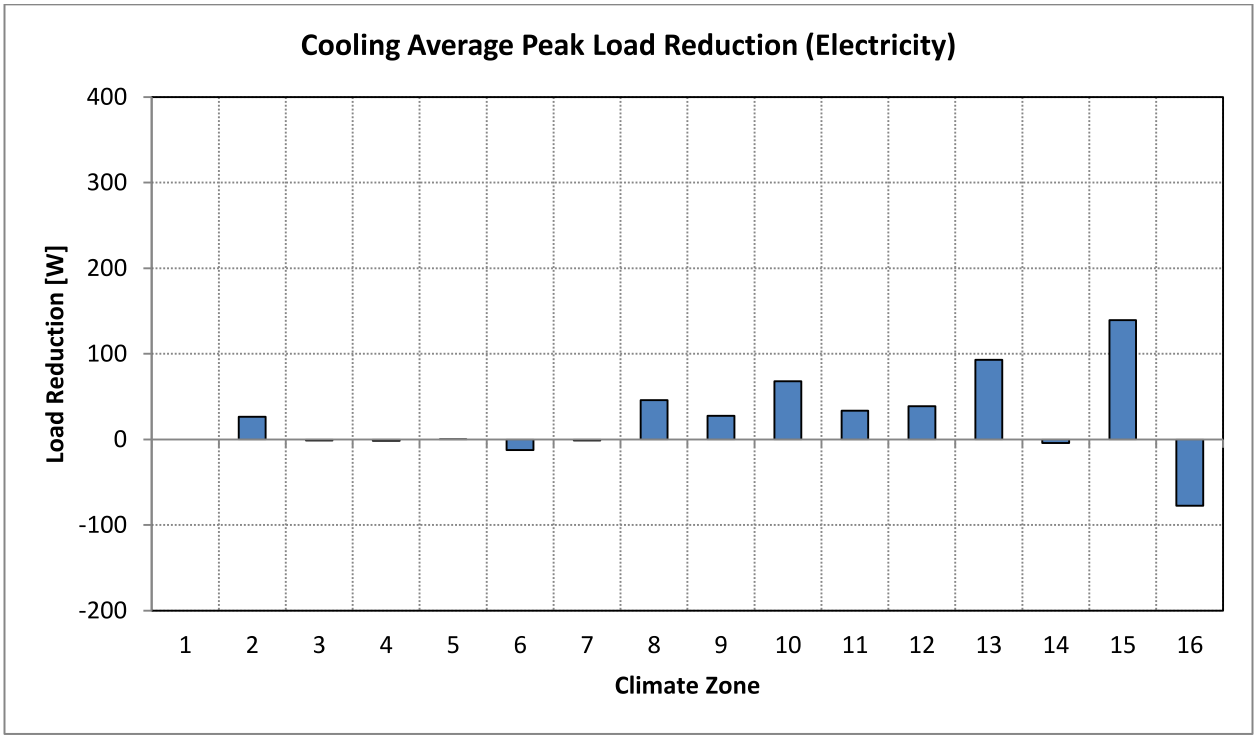


Figure 26: Cooling average peak load reduction over the year from using RIVEC (whole-house exhaust, Prototype C, medium leakage)

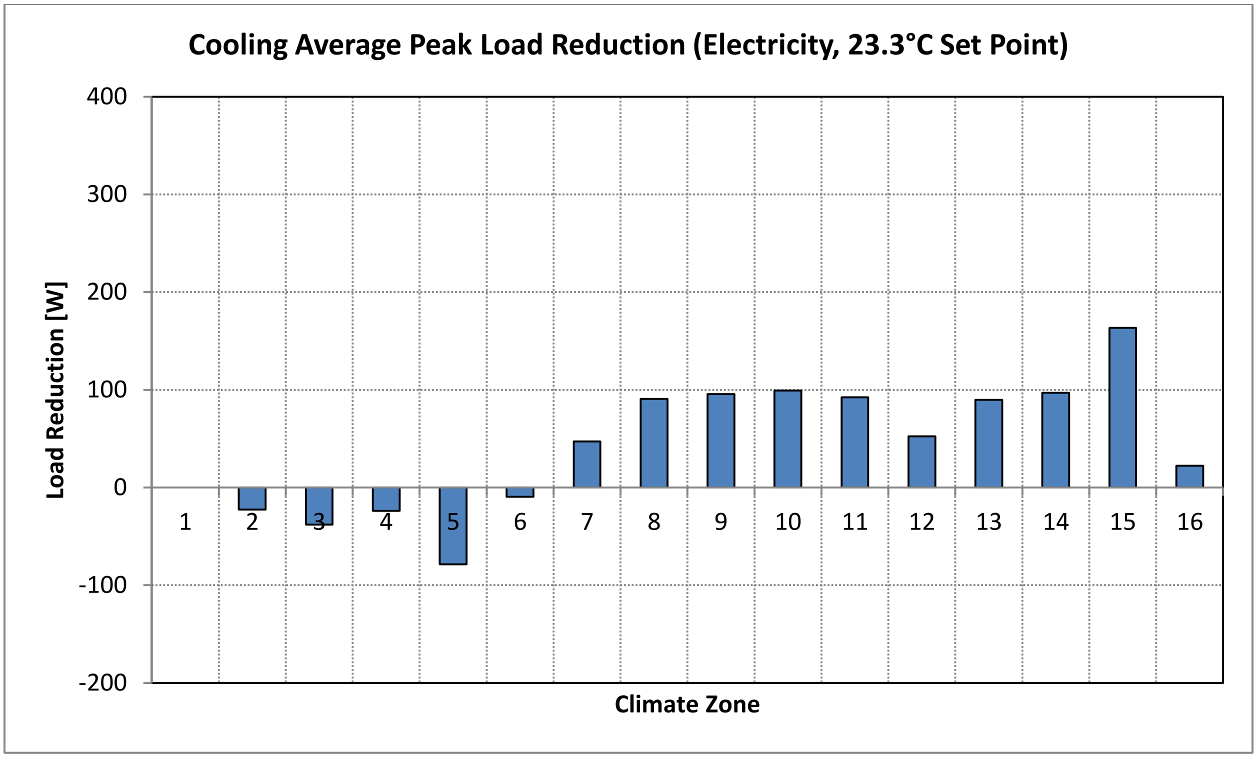


Figure 27: Cooling average peak load reduction over the year using RIVEC with a cooling set point of 74°F (whole-house exhaust, Prototype C, medium leakage). Note climate zone 1 has been omitted due to only one cooling day

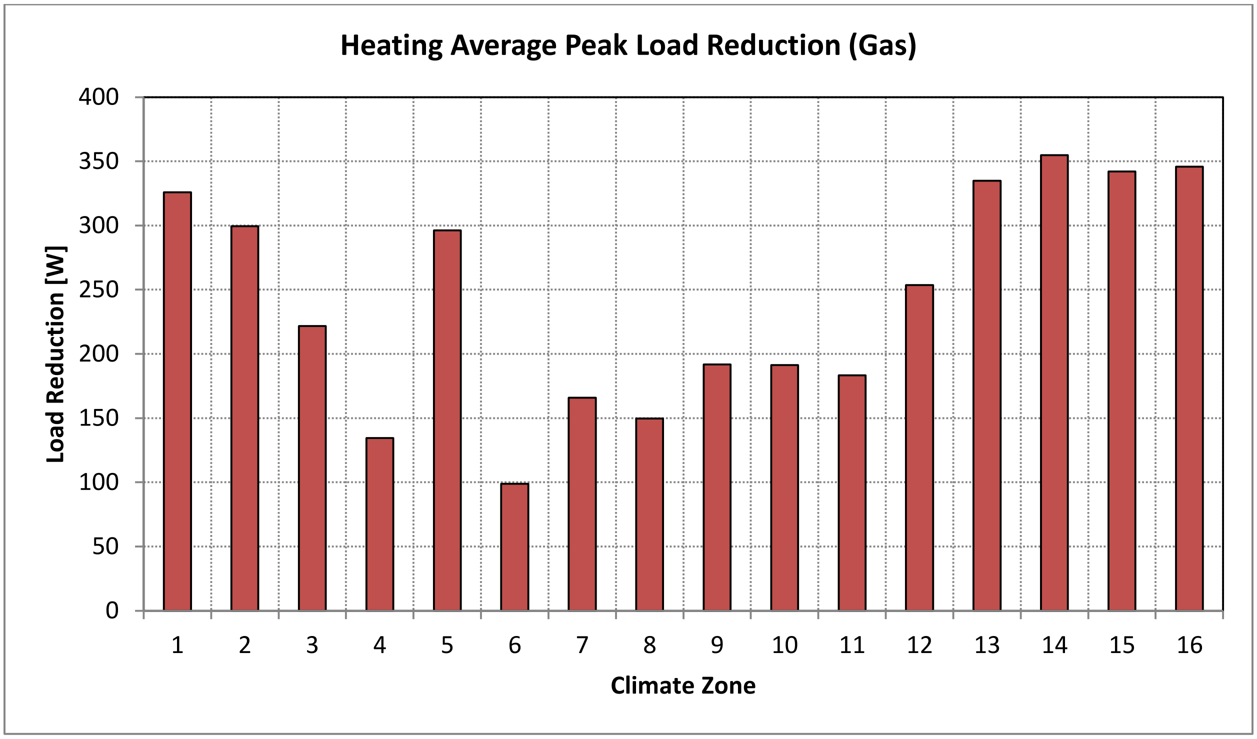


Figure 28: Heating average peak load reduction over the year from using RIVEC (whole-house exhaust, Prototype C, medium leakage)

Figure 26 shows the annual average cooling peak reduction with the Title 24 set points. Again, the Title 24 thermostat set points mean there is very little potential for cooling peak savings. Figure 27 shows the annual average cooling peak reduction with the 23.3°C set point. Climate zone 1 (Arcata) only has one cooling day and so the result was omitted as no meaningful average may be taken. The average cooling peak reductions for climate zones 2 to 6 are negative (i.e. RIVEC caused more energy to be used). This is because these climate zones are along the coast and have solar driven loads that peak around midday. The utility-defined cooling peak used for this analysis is 2 pm to 6 pm when the outdoor air temperature in these zones is typically cooler than the indoor temperature. Therefore, shutting off the ventilation system reduces the potential for ventilation cooling and causes the air conditioner to run more often under RIVEC. This indicates that improvements may be made to the RIVEC algorithm to take advantage of ventilation cooling. These climate zones also have very low cooling demands e.g. there are only five cooling peak periods (equal to 20 hours) in climate zone 5 – Santa Maria – over the entire year.

Away from the coast, in the hotter climates, there are potential for savings using RIVEC. In climate zone 15 (El Centro) the annual average cooling peak saving is 163 W. The average cooling peak reduction for the non-coastal climate zones (8 to 16) is 89 W.

Figure 28 shows that heating annual average load reductions are common for all 16 California climate zones. The annual heating peak savings are a lot less sensitive to equipment sizing and thermostat set points than cooling. The highest power reduction (355 W) is in climate zone 14, China Lake. The lowest (99 W) is in climate zone 6, Los Angeles. On average, across all climate zones, RIVEC removes 243 W from the heating peak period over the year.

7. CONCLUSIONS

The RIVEC advanced ventilation controller will:

- typically reduce the ventilation-related energy from whole-house ventilation systems by at least 40%, while maintaining equivalence to ASHRAE Standard 62.2
- not introduce any problems with acute exposures to constantly-emitted indoor pollutants
- provide ventilation energy reductions that are robust across climate, house size and air leakage
- provide absolute energy savings per household of 500 to 7,500 kWh/year depending on climate – with more temperate climates at the lower end of energy savings estimates
- allow significant peak power reductions of up to 2 kW for a typical home

Passive and hybrid ventilation systems need to be sized appropriately. The conservative approach used in this study, where the number of hours of the year where the passive stack airflow met or exceeded ASHREAE 62.2 was maximized (80%), could be optimized further to reduce energy use.

The passive systems met annual average (ASHRAE 62.2) and hourly (standards for acute exposure) requirements for ventilation.

Hybrid systems and airflow control measures for passive systems showed the potential to limit excess energy use due to over-ventilation. However, without controls the energy penalty due to over-ventilation in passive systems was significant in climates with extreme weather.

The RIVEC algorithm may be further improved by taking greater advantage of both economizer operation and the potential for ventilation cooling.

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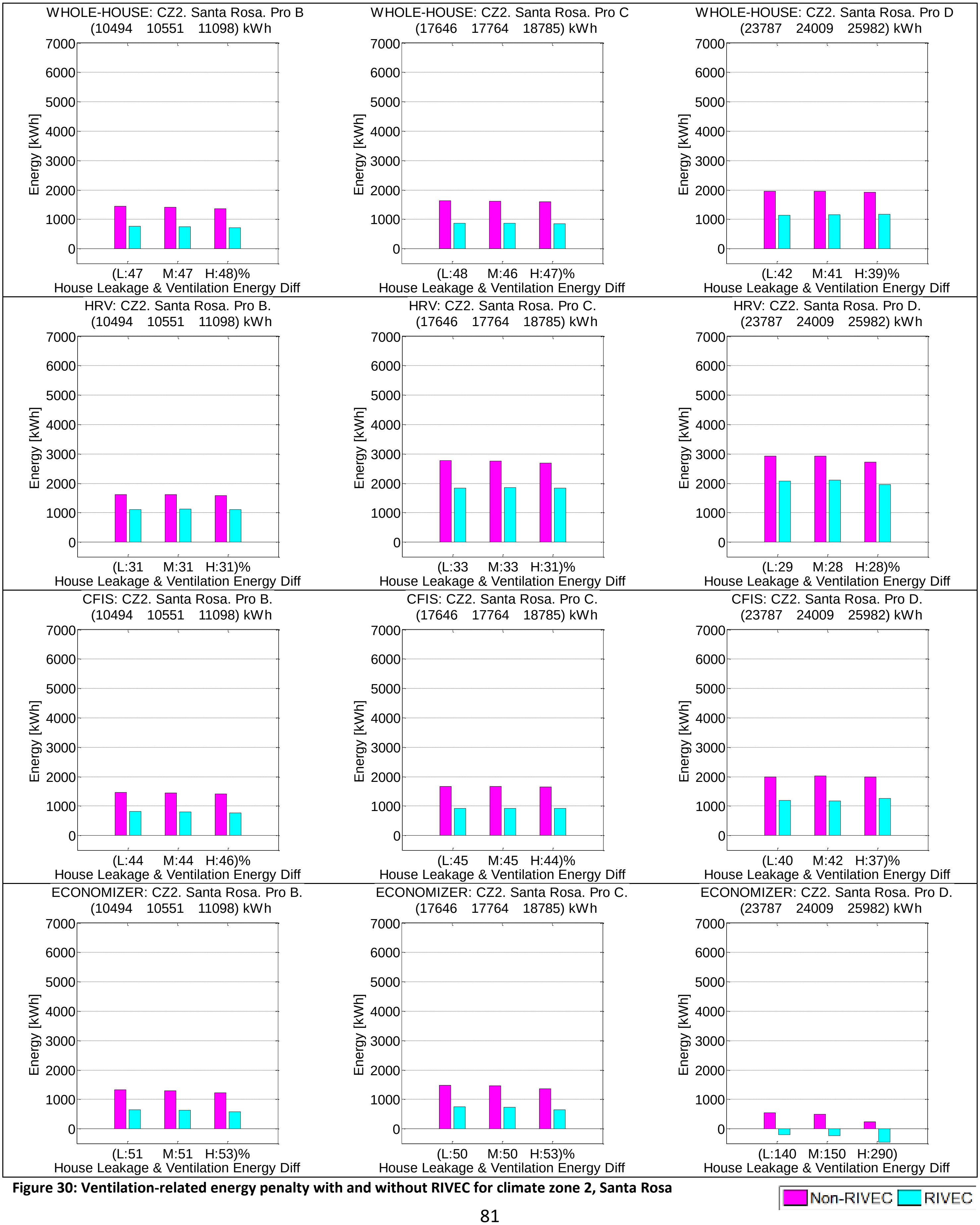
Appendix A: Reduction in Ventilation-Related Energy from using RIVEC with Whole-House Mechanical Ventilation Systems

Ventilation strategies 1 to 4 (mechanical ventilation strategies only). Figure 29 to Figure 44 show the additional energy consumed due to adding a whole-house mechanical ventilation system with (pink) and without (light blue) RIVEC. They are arranged by climate zone. Each individual graph shows the additional energy used for one house size with three different envelope leakages:

Low (L)	4.8 ACH_{50}
Medium (M)	5.2 ACH_{50}
High (H)	8.6 ACH_{50}

The energy [kWh] used by the reference case (Strategy 0) houses with no whole-house mechanical ventilation is contained in parentheses in order of envelope leakage level, underneath the figure title. The percentage of total ventilation energy saved is in parentheses above the x-axis label.

Figure 29: Ventilation-related energy penalty with and without RIVEC for climate zone 1, Arcata


WHOLE-HOUSE: CZ2. Santa Rosa. Pro B (10494 10551 11098) kWh

WHOLE-HOUSE: CZ2. Santa Rosa. Pro C (17646 17764 18785) kWh

WHOLE-HOUSE: CZ2. Santa Rosa. Pro D (23787 24009 25982) kWh

HRV: CZ2. Santa Rosa. Pro B. (10494 10551 11098) kWh

HRV: CZ2. Santa Rosa. Pro C. (17646 17764 18785) kWh

HRV: CZ2. Santa Rosa. Pro D. (23787 24009 25982) kWh

CFIS: CZ2. Santa Rosa. Pro B. (10494 10551 11098) kWh

CFIS: CZ2. Santa Rosa. Pro C. (17646 17764 18785) kWh

CFIS: CZ2. Santa Rosa. Pro D. (23787 24009 25982) kWh

ECONOMIZER: CZ2. Santa Rosa. Pro B. (10494 10551 11098) kWh

ECONOMIZER: CZ2. Santa Rosa. Pro C. (17646 17764 18785) kWh

ECONOMIZER: CZ2. Santa Rosa. Pro D. (23787 24009 25982) kWh

Figure 30: Ventilation-related energy penalty with and without RIVEC for climate zone 2, Santa Rosa

Figure 31: Ventilation-related energy penalty with and without RIVEC for climate zone 3, Oakland


WHOLE-HOUSE: CZ4. Sunnyvale. Pro B. (7736 7792 8199) kWh

WHOLE-HOUSE: CZ4. Sunnyvale. Pro C. (12930 13018 13837) kWh

WHOLE-HOUSE: CZ4. Sunnyvale. Pro D. (16584 16759 18244) kWh

HRV: CZ4. Sunnyvale. Pro B. (7736 7792 8199) kWh

HRV: CZ4. Sunnyvale. Pro C. (12930 13018 13837) kWh

HRV: CZ4. Sunnyvale. Pro D. (16584 16759 18244) kWh

CFIS: CZ4. Sunnyvale. Pro B. (7736 7792 8199) kWh

CFIS: CZ4. Sunnyvale. Pro C. (12930 13018 13837) kWh

CFIS: CZ4. Sunnyvale. Pro D. (16584 16759 18244) kWh

ECONOMIZER: CZ4. Sunnyvale. Pro B. (7736 7792 8199) kWh

ECONOMIZER: CZ4. Sunnyvale. Pro C. (12930 13018 13837) kWh

ECONOMIZER: CZ4. Sunnyvale. Pro D. (16584 16759 18244) kWh

Figure 32: Ventilation-related energy penalty with and without RIVEC for climate zone 4, Sunnyvale

Figure 33: Ventilation-related energy penalty with and without RIVEC for climate zone 5, Santa Maria

Figure 34: Ventilation-related energy penalty with and without RIVEC for climate zone 6, Los Angeles

Figure 35: Ventilation-related energy penalty with and without RIVEC for climate zone 7, San Diego

Figure 36: Ventilation-related energy penalty with and without RIVEC for climate zone 8, El Toro

🟪 Non-RIVEC 🟦 RIVEC

Figure 37: Ventilation-related energy penalty with and without RIVEC for climate zone 9, Burbank


WHOLE-HOUSE: CZ10. Riverside. Pro B. (6205 6234 6513) kWh

WHOLE-HOUSE: CZ10. Riverside. Pro C. (10236 10292 10842) kWh

WHOLE-HOUSE: CZ10. Riverside. Pro D. (13352 13457 14512) kWh

HRV: CZ10. Riverside. Pro B. (6205 6234 6513) kWh

HRV: CZ10. Riverside. Pro C. (10236 10292 10842) kWh

HRV: CZ10. Riverside. Pro D. (13352 13457 14512) kWh

CFIS: CZ10. Riverside. Pro B. (6205 6234 6513) kWh

CFIS: CZ10. Riverside. Pro C. (10236 10292 10842) kWh

CFIS: CZ10. Riverside. Pro D. (13352 13457 14512) kWh

ECONOMIZER: CZ10. Riverside. Pro B. (6205 6234 6513) kWh

ECONOMIZER: CZ10. Riverside. Pro C. (10236 10292 10842) kWh

ECONOMIZER: CZ10. Riverside. Pro D. (13352 13457 14512) kWh

Figure 38: Ventilation-related energy penalty with and without RIVEC for climate zone 10, Riverside

Figure 39: Ventilation-related energy penalty with and without RIVEC for climate zone 11, Red Bluff

🟪 Non-RIVEC 🟦 RIVEC

Figure 40: Ventilation-related energy penalty with and without RIVEC for climate zone 12, Sacramento

Figure 41: Ventilation-related energy penalty with and without RIVEC for climate zone 13, Fresno

🟪 Non-RIVEC 🟦 RIVEC

Figure 42: Ventilation-related energy penalty with and without RIVEC for climate zone 14, China Lake

Figure 43: Ventilation-related energy penalty with and without RIVEC for climate zone 15, El Centro

Figure 44: Ventilation-related energy penalty with and without RIVEC for climate zone 16, Mount Shasta

🟪 Non-RIVEC 🟦 RIVEC

Appendix B: Passive and Hybrid Ventilation-Related Energy

Figure 45 and Figure 46 show the additional ventilation-related energy from adding a:

- mechanical whole-house exhaust ventilation system (blue)
- passive stack (or stacks) sized to meet the ASHRAE 62.2 minimum ventilation rate for at least 80% of the year (green)
- passive stack (or stacks) over-sized and flow limited to 125% ASHRAE 62.2 minimum airflow rate (red)
- hybrid system comprising of a passive stack flow limited to 100% of the ASHRAE 62.2 minimum airflow rate, and a whole-house exhaust fan controlled by RIVEC (yellow)

Results are for the three house sizes. Figure 45 shows the houses with envelope leakage of 4.8 ACH_{50} and Figure 46 shows the houses with an envelope leakage of 8.6 ACH_{50}. For the 5.2 ACH50 results see Figure 22 in the main body of the text.

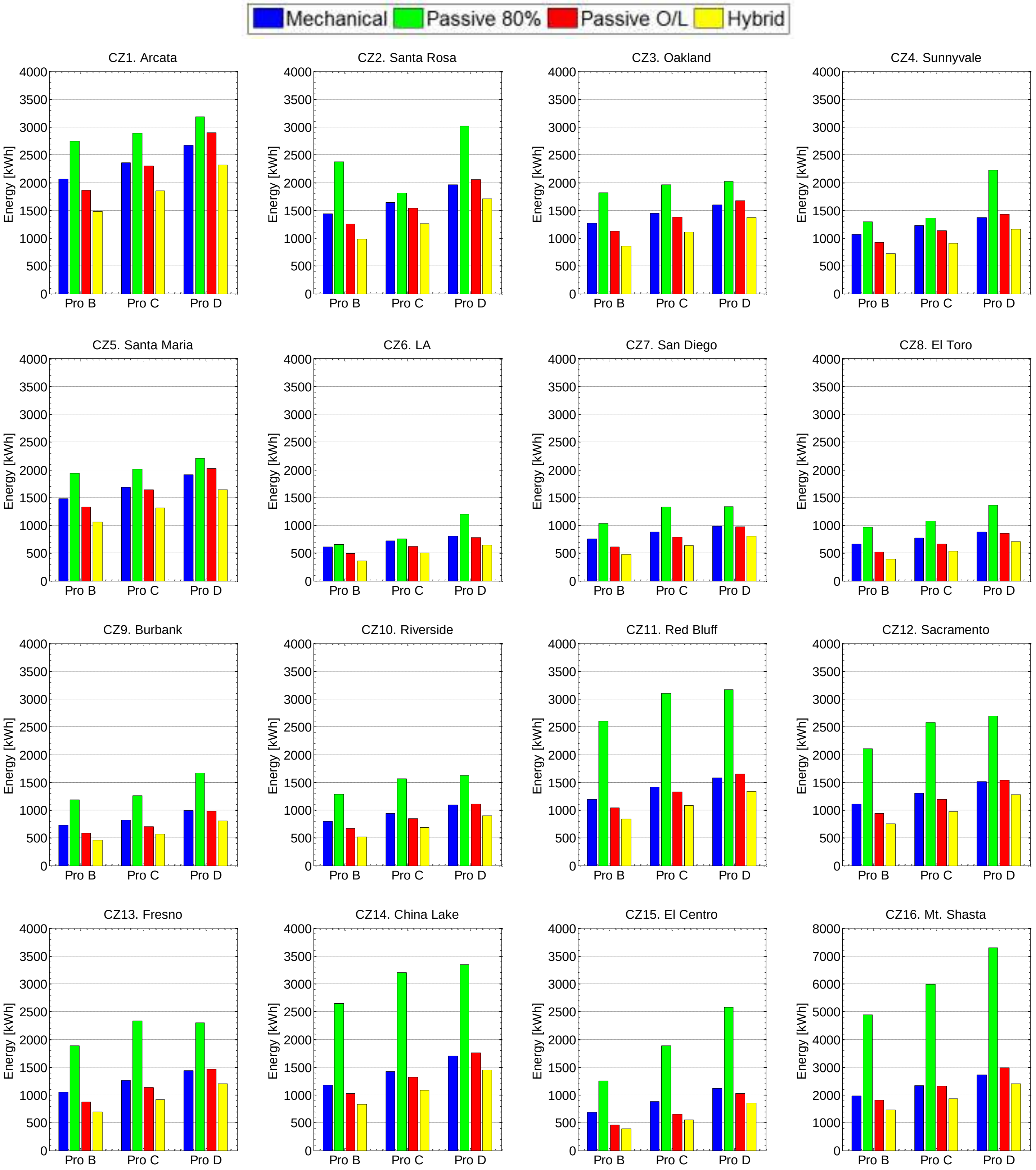


Figure 45: Ventilation-related energy incurred from adding whole-house ventilation (mechanical, passive, passive oversized and limited, and hybrid). Envelope Leakage = 4.8 ACH_{50}

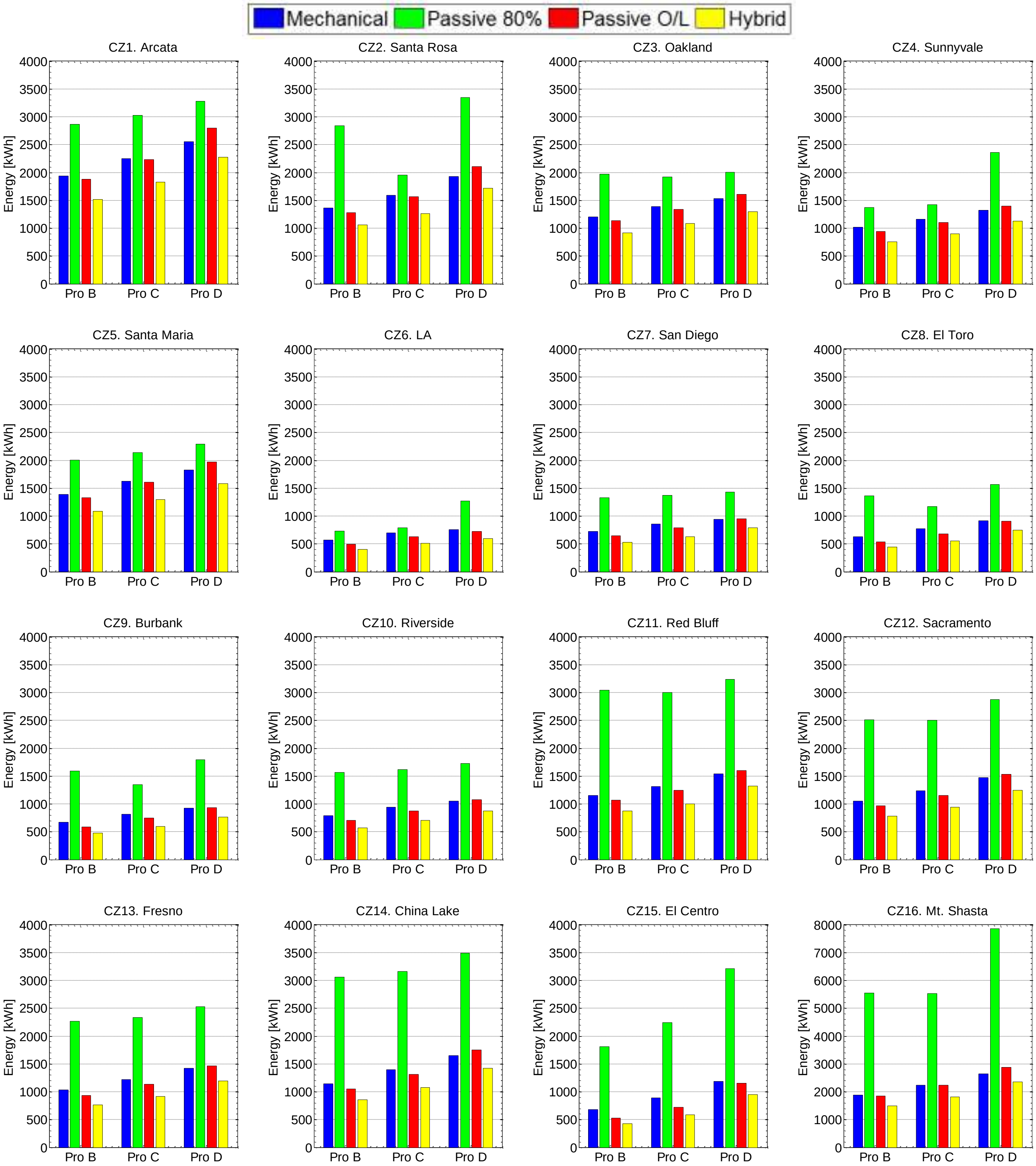


Figure 46: Ventilation-related energy incurred from adding whole-house ventilation (mechanical, passive, passive oversized and limited, and hybrid). Envelope Leakage = 8.6 ACH$_{50}$

Appendix C: Critical Peak Load Reduction

Table 24: Heating critical peak load reduction [W]

House	Leakage	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Prototype B	4.8	10	10	10	10	10	10	10	10	10	366	10	10	122	756	1046	605
	5.2	10	64	10	10	10	10	10	10	10	248	10	10	457	699	1194	546
	8.6	59	10	96	10	10	10	10	10	10	10	10	10	848	68	1194	129
Prototype C	4.8	97	12	12	12	359	12	12	12	12	12	12	12	305	1820	1825	220
	5.2	97	12	12	12	185	12	12	12	12	358	94	12	12	1418	918	324
	8.6	97	12	87	12	12	79	12	12	12	12	177	182	1185	1720	1566	532
Prototype D	4.8	3290	133	1272	388	2803	1564	12	1155	1796	546	4359	3071	640	1949	2009	2020
	5.2	3400	740	1853	388	1351	1822	173	1331	2830	902	2769	2634	640	1045	1011	547
	8.6	2088	618	981	576	2245	1046	253	100	1139	635	2345	3290	640	658	2176	-256

Table 25: Furnace fractional run times during critical peak hours

House	Leakage	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*
Prototype B	4.8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00	0.99	0.96	0.66	0.97
	5.2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00	0.97	0.96	0.64	0.97
	8.6	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.95	1.00	0.65	0.99
Prototype C	4.8	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.94	0.64	0.99
	5.2	1.00	1.00	1.00	1.00	0.99	1.00	1.00	1.00	1.00	0.98	1.00	1.00	1.00	0.95	0.68	0.99
	8.6	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	0.96	0.94	0.66	0.98
Prototype D	4.8	0.76	0.78	0.95	0.99	0.74	0.94	1.00	0.96	0.90	0.98	0.76	0.76	0.73	0.74	0.46	0.73
	5.2	0.72	0.77	0.93	0.99	0.78	0.92	0.99	0.95	0.86	0.97	0.82	0.76	0.73	0.76	0.46	0.78
	8.6	0.80	0.80	0.95	0.98	0.78	0.96	0.99	1.00	0.95	0.98	0.87	0.77	0.77	0.79	0.47	0.84

Table 26: Cooling critical peak load reduction [W]

House	Leakage	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	0	52	-12	-2	118	-12	410	0	10	8	17	10	105	8	156	41
	5.2	0	38	-11	-1	106	-19	438	0	11	8	6	12	98	8	301	41
	8.6	0	61	-4	2	13	-9	46	2	17	8	16	15	10	9	170	41
Prototype C	4.8	0	32	-22	-1	0	-15	-4	25	11	8	20	19	198	23	541	59
	5.2	0	33	-20	0	0	-13	4	25	12	8	18	20	68	23	338	57
	8.6	0	36	-7	7	3	6	4	23	14	7	22	22	260	15	348	33
Prototype D	4.8	0	36	-12	-3	-9	-7	1	155	131	165	13	17	790	15	826	86
	5.2	0	35	-11	-3	-11	-6	5	134	29	309	490	23	193	15	759	85
	8.6	0	31	-1	0	-27	8	15	193	24	143	221	19	205	16	729	80

Table 27: Compressor fractional run times during critical peak hours

House	Leakage	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***
Prototype B	4.8	0.00	0.99	1.00	1.00	0.40	1.00	0.79	1.00	1.00	1.00	1.00	1.00	0.98	1.00	0.98	1.00
	5.2	0.00	0.99	1.00	1.00	0.40	1.00	0.78	1.00	1.00	1.00	1.00	1.00	0.98	1.00	0.96	1.00
	8.6	0.00	0.98	1.00	1.00	0.25	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00
Prototype C	4.8	0.00	1.00	1.00	1.00	0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	0.95	1.00
	5.2	0.00	1.00	1.00	1.00	0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	0.97	1.00
	8.6	0.00	1.00	1.00	1.00	0.25	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	0.97	1.00
Prototype D	4.8	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	0.98	0.98	1.00	1.00	0.90	1.00	0.91	1.00
	5.2	0.00	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	0.96	0.93	1.00	0.98	1.00	0.94	1.00
	8.6	0.00	1.00	1.00	1.00	0.99	1.00	1.00	0.97	1.00	0.98	0.97	1.00	0.98	1.00	0.95	1.00