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Development of a Residential Integrated Ventilation Controller

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Abstract

The goal of this study was to develop a Residential Integrated Ventilation Controller (RIVEC) to reduce the energy impact of required mechanical ventilation by 20%, maintain or improve indoor air quality and provide demand response benefits.   This represents potential energy savings of about 140 GWh of electricity and 83 million therms of natural gas as well as proportional peak savings in California. The RIVEC controller is intended to meet the 2008 Title 24 requirements for residential ventilation as well as taking into account the issues of outdoor conditions, other ventilation devices (including economizers), peak demand concerns and occupant preferences. The controller is designed to manage all the residential ventilation systems that are currently available. A key innovation in this controller is the ability to implement 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.   Simulations, based on the ones used to develop the new residential ventilation requirements for the California Buildings Energy code, were used to further define the specific criteria and strategies needed for the controller.   These simulations provide estimates of the energy, peak power and contaminant improvement possible for different California climates for the various ventilation systems. Results from a field test of the prototype controller corroborate the predicted performance.

Key Words: Residential ventilation, ventilation controller, ASHRAE Standard 62.2, California Title 24

Introduction

Indoor air quality (IAQ) is a complex result of occupant activities, human responses, source emission, and contaminant removal. The key issues that one can set requirements for 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.

Virtually every building code has requirements in it related to ventilation and indoor air quality, but an integrated approach to looking at residential indoor air quality is usually lacking. The nation's only consensus standard on residential ventilation and indoor air quality is published by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ANSI/ASHRAE Standard 62.2-2010).

Increasingly, building codes and standards require that homes have mechanical ventilation to provide acceptable indoor air quality. 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. 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 (e.g. a vented clothes dryer) or the presence of outdoor air pollutants such as ozone or particulates. 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 indoor air quality (IAQ) impacts. This report discusses the initial development of a prototype Residential Integrated Ventilation Energy Controller (RIVEC) that optimizes these operating costs and air quality issues.

This study took two approaches to evaluating the RIVEC. The first was to install a prototype in a home and monitor its operation together with climate data and the operation of related HVAC systems. The second was to extend the evaluation to a wider range of homes and climates by simulation using software developed by LBNL specifically for evaluation of residential HVAC systems.

State-of-the-Art in Residential Ventilation

Whole-house mechanical ventilation has not been a common technology in homes in the US. Only recently has the need for designed mechanical ventilation in homes become generally accepted. The current state of the art in providing this ventilation is relatively crude and treats the whole-house mechanical ventilation system in isolation and independent of other air moving devices in the home. Because it does not consider the house as a system, it fails to take advantage of synergies that can provide many benefits.

The controller being developed is intended to meet the ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) Standard 62.2 requirements for residential ventilation as well as taking into account the issues of outdoor conditions, other ventilation devices (including economizers), peak demand concerns and occupant preferences. The controller is designed to manage all of the residential ventilation systems that are currently on the market.

The basic requirement for ASHRAE Standard 62.2 is that there be mechanical ventilation operating at a rate equal to 1 cubic feet per minute (cfm) per hundred square feet of floor area (0.05 L/s) plus 7.5 cfm (3.5 L/s) per person where the number of people is presumed to be equal to one more than the number of bedrooms.

There is another requirement that kitchens and bathrooms be equipped with exhaust fans equal to 100 cfm and 50 cfm (50 L/s and 25 L/s) respectively. There are additional requirements regarding source control, properties of mechanical equipment, commissioning, etc. These properties do not impact the controller or the simulations and so will not be repeated here. The reader is directed to the standard and its associated users guide (ASHRAE 2007) for further information.

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 incidentally ventilate (such as bath fans, 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 system.

A key innovation in RIVEC is the ability to implement 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 uses the full generalization of that method. The key equations of intermittent ventilation define the efficacy of ventilation as it relates to the pattern of ventilation.

The temporal ventilation effectiveness, i.e. 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}), 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}):

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

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:

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

where "coth" in Figure 2 is the hyperbolic cotangent and the nominal turn-over, *N*, is defined as follows:

$$\mathrm{N} \equiv \frac{(A_{eq} - A_{low}) \cdot T_{cycle}}{2} \tag{3}$$

where T_{cycle} is the length of a cycle (typically this will be the sum of the time of operation at higher and lower air flows). 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 other 20 hours. Using the rates of 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 indoor air quality. 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 turn-over time, τ_e:

$$\tau_e(t) = \int_{-\infty}^{t} e^{\int_t^{t'} A(t'')dt''} dt' \tag{4}$$

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 times the instantaneous turn-over:

$$R(t) = A_{eq} \tau_e(t) \tag{5}$$

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:

$$d = \frac{1}{T} \int_0^T R(t)dt = 1/\varepsilon = A_{eq} \bar{\tau} \tag{6}$$

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 our purposes it is more useful to use recursive formula for discrete data. We can rewrite the expression for turn-over time as follows:

$$\tau_i = \frac{1-e^{-A_i \Delta t}}{A_i} + \tau_{i-1} e^{-A_i \Delta t} \tag{7}$$

For our intermittent ventilation ("notch") strategy the relative exposure, calculated from the discrete turn-over time, has a minimum near 0.8 just before the notch time and a value of twice that at the end of the notch time. These values will be helpful in the design of the RIVEC controller.

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.

$$d_i = A_{eq} \tau_i (1-e^{-\Delta t/24hrs}) + d_{i-1} e^{-\Delta t/24hrs} \tag{8}$$

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. This control algorithm is proprietary.

Envelope air leakage, or more properly the infiltration it causes, contributes to total ventilation and is also a thermal load on the house. The prescriptive path in standard 62.2 does not require any modification to the mechanical ventilation rate based on envelope air leakage. While it is true that a leakier house will generally use more energy annually, the performance of the RIVEC controller is not going to be highly dependent on this factor. Although the RIVEC controller with ignore the impacts of air leakage, the simulations will include the envelope air leakage when determining overall ventilation rates and energy impacts. Similarly duct leakage can induce extra infiltration and substantial energy penalties, but we will not parametrically examine the impacts of duct leakage in this study.

A secondary innovation is the ability of this controller to handle a wide range of ventilation systems in the same way a thermostat can handle a wide range of HVAC equipment. Some ventilation systems have (or will soon have) dedicated controllers but they do not interface with other HVAC components and they are designed to handle a very specific ventilation system only.

Ventilation

ASHRAE Standard 62.2-2010 provides the industry standard for minimum ventilation rates in both new and existing homes. From the State energy code perspective, efforts should focus on finding the most energy-efficient means to provide the minimum ventilation rates in this national consensus standard. Developing and/or determining optimal ventilation systems has been an area of research for many years (e.g. Feustel 1986). However, changes in energy costs, the tightness of envelopes and pollutant sources within the housing stock, and the availability of technology have made selection of optimal ventilation systems a moving target.

Sherman and Matson (1997) performed an analysis to assess the optimal ventilation strategy for houses that were intended to meet both an air tightness standard and a ventilation standard. The three main ventilation strategies in use at the time were considered: natural ventilation, central exhaust, and air-to-air heat exchangers. The analysis estimated that for with leaky houses 60% of the ventilation/infiltration energy requirement could be cost-effectively saved without using heat recovery, just by tightening the envelope and, if necessary, by adding a right-sized mechanical system. To take full advantage of a heat-recovery ventilation system, it is often necessary to make the building envelope substantially tighter than typical of new home construction.

Air Tightness

Increasing air tightness in homes has led to the need for mechanical ventilation. In the 1980s researchers realized that houses were very leaky and represented a huge opportunity for energy savings, but people really had no idea what the stock looked like, let alone how the leakage was distributed. For example, weatherization practitioners (and window and weather-stripping manufacturers) used to say that windows and doors were the source of leakage. When researchers finally did component leakage tests, they found that doors and windows were only about 20% of the issue. The rest of the leakage was in envelope penetrations and construction details such as sill plates.

More recent work by LBNL (Sherman and Matson (2002)) has shown that newer homes are much tighter than the older houses in the stock, but the downward trend had stopped. This level of air tightness certainly means that new houses are not generally going to be excessively leaky, but this level of leakage does cause several problems. At this level of leakage, there will be insufficient ventilation (from infiltration) to meet ventilation standards. Thus, people either need to dutifully open their windows or they need designed ventilation systems. Price and Sherman (2006) have shown that people in new, tighter California houses do not open their windows sufficiently to provide adequate ventilation. At the same time, this level of infiltration is sufficiently large that many of the most energy efficient systems (i.e., ERV or HRV systems) will not work well.

Mechanical Ventilation Systems

A wide variety of ventilation systems are available to be used and they have been reviewed by Russell et al. (2005). Systems of interest to the CEC have been simulated by

Walker and Sherman (2006) to determine their performance with respect to the anticipated requirements in the 2008 Residential Energy Standards for California. These systems were:

- Continuous exhaust[1]
- Intermittent exhaust[2]
- Heat recovery ventilator
- Central Fan Integrated (CFI) Supply with air inlet in return and continuously operating exhaust (several CFI combinations were studied)
- Continuous Supply

The results of the Walker and Sherman study show that systems with smart controllers can offer substantial energy savings compared to the simplest systems that run continuously. The magnitude of the savings depend on climate, but are typically TDV$500. TDV stands for Time Dependent Valuation and allows the price of electricity to vary with demand. The Energy Commission has standard TDV profiles that were used to make these estimates. The peak demand reductions are about 500W.

Some systems currently on the market use electronic controllers to manage the ventilation system. These controllers focus only on the ventilation system and are predominantly for use in the central-fan integrated supply systems such as those sold by Honeywell, and Aprilaire. For controlling exhaust fans, Tamarack makes a combined timer and flow control. The Davis Energy Group has a proprietary product, NightBreeze, that is intended to provide ventilative cooling and/or evaporative cooling; it has the potential for being used as an Indoor Air Quality (IAQ) control device, but is not yet used that way.

These controllers are explicitly designed to work with only one type and style of mechanical ventilation system and are not designed to be demand responsive or to interface with other whole-ventilation equipment such as economizers.

The following systems are those typically found in new homes that are ASHRAE 62.2 compliant.

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[1] "Continuous Exhaust" is continuous as far as the user is concerned in that it is "on" all the time. It may, however, be temporarily shut off by RIVEC when the controller determines it is not necessary for a period of time.

[2] "Intermittent exhaust" is normally controlled by an independent timer of some sort on a fixed schedule. We have subsumed the basic operating strategy by including a 4-hour off period in RIVEC so this approach will not be extensively investigated in this report as it is somewhat redundant.

Exhaust

In this system the primary whole-house ventilation technology is an exhaust fan. In the default configuration, the fan is run continuously in at the rate specified by Standard 62.2. The fan may be a double-duty fan because it is in, for example, a bathroom and meets the local exhaust requirement of ASHRAE 62.2 as well, but we will treat it as a stand-alone fan in this study.

Supply

In this system, the primary whole-house ventilation technology is a dedicated supply system that dilutes outdoor air and supplies it to habitable rooms. It is not commonly used but makes sense in homes without a central air system. It requires that the outdoor air be blended with indoor air to temper it before delivering it to the habitable spaces.

Heat Recovery Ventilator (HRV)

In this system, the primary whole-house ventilation technology is a balance system with a heat recovery ventilator integrated into the HVAC system. This system provides heat recovery. The most common installation, which is the one we will design for, has the HRV sized significantly larger than the 62.2 rate (e.g. by a factor of 3) and interconnected with the air handler; it then it cycles with a timer to get the ASHRAE 62.2 minimum flow. This is how the reference state will be treated, but RIVEC will take over cycling the HRV to maintain the correct ventilation rate.

Exhaust with Central Fan Integrated Supply and Mixing (CFI)

This is similar to the first system except it has an inlet duct to the return plenum to pull in and distribute outdoor air when the central air handler is operating. In addition, this system assures that the air handler operates at least 1/3 of the time—even if there is no call for heating or cooling. This system provides the extra service of air distribution.

For the purposes of this report, we assume that every house has exactly one of the four types of mechanical ventilation systems listed above. Depending on the system there may be multiple pieces of that system that needs to be controlled and there may be multiple levels of ventilation possible out of that system.

Exogenous Mechanical Ventilation

Although there may be only one 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. The RIVEC controller will monitor many of these exogenous systems and take into account their impacts thereby lessening the need for additional mechanical ventilation.

The systems that RIVEC can monitor include the following:

Clothes Dryers

According to 62.2 clothes dryers must be vented 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.

Economizers and/or direct evaporative coolers

In dry climates with large diurnal temperature swings, residential economizers and (direct) evaporative coolers have a large potential for reducing cooling energy. Incidentally, these technologies provide an order of magnitude more whole-house ventilation than is required by 62.2. Not only can the regular whole-house system be turned off when these large system run, but "credit" can be taken for several hours afterwards.

Bath and kitchen exhaust fans

Kitchen and bath fans can provide significant ventilation when operated. Households use these fans in different ways, which must be monitored in real time by RIVEC.

Central Fan Integrated Supply systems used for air distribution

The central-fan integrated supply system operates autonomously to provide fresh air distribution to the habitable rooms. This is a service above that required by Title 24 or 62.2 and therefore will not be under the control of RIVEC. Since this is an additional occupant service, we will assume for the purposes of this project that it is provides exogenous mechanical supply ventilation. In principle we could apply it as an option to other mechanical ventilation strategies, but as a practical matter no one has done so; nor is anyone recommending it.

Prototype Evaluation

1. Field Testing A Prototype Controller

The controller had the following components:

- A means of sensing the operation of devices that incidentally provide mechanical ventilation
- A means of controlling the whole-house mechanical ventilation system.
- A means of implementing the RIVEC algorithm based on system operation

A simple interface was developed (see Figure 3 for an illustration) in order to enter the data needed for RIVEC operation:

The Basic data include:

- House information
- Defining the RIVEC controlled ventilation system
- Defining the ventilation systems present in the house
- Defining peak hours and seasons
- Setting the target (ASHRAE 62.2) ventilation rate

Details of the implementation of this task are proprietary, pending patent protection.

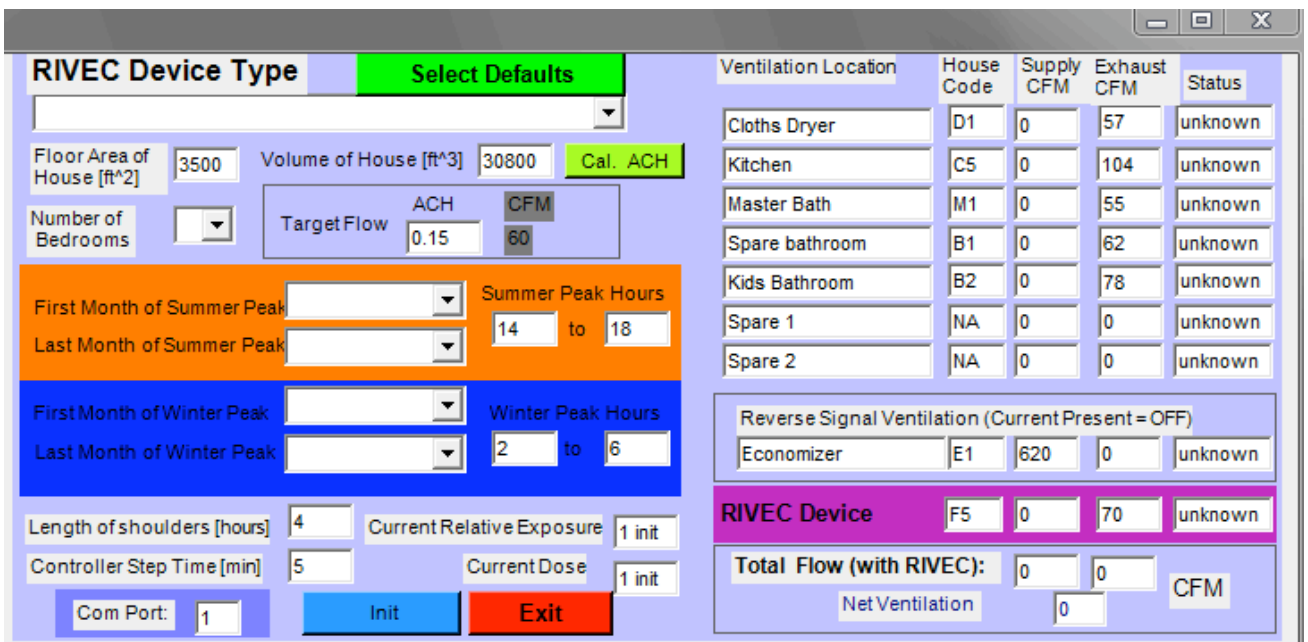

Figure 1. Sample Input data interface for RIVEC controller.

One test home was selected to demonstrate the ventilation controller. The test home was located in Moraga, CA and occupied by a family of four and had an ASHRAE 62.2 compliant ventilation system and an economizer. Preliminary characterization of the test site included envelope and duct leakage, ventilation rate and other house characteristics. These characteristics were also used as input to the simulations.

Moraga Home Characteristics

Floor plans were used to determine the floor area of 3400 ft^2 (317 m^2).

Measured ceiling heights (the house had several cathedral ceiling rooms) were used to determine the house volume of 29700 ft^3 (841 m^3).

The overall thermal conductivity (UA) of the home was estimated based on measured wall and window areas and thermal characteristics[3] to be 887 W/K.

The house is laid out on a north-south axis. This is reflected in the window orientations (that determine solar gain) and the leakage distribution (the leakage was assumed to be evenly distributed with wall area). The window areas for each orientation were: 43 m^2 facing west or east, 4.9 m^2 facing north and 6.2 m^2 facing south and the wall leakage was 35% in each of the long faces of the home and 15% in the other two.

The envelope leakage was determined from a blower door test and was 0.209 m^3/sPa^n (about 5900 cfm50) with a pressure exponent of 0.66.

The home is relatively well sheltered from the wind by neighboring homes and trees.

The home was heated and cooled by two separate systems – one for each end of the house. The duct leakage was combined for the two systems and was measured using a DeltaQ test (following ASTM E1554). The results were 17% for supply and 20% for return (the return did include a minimum outside air vent whose measured air flow was 5 to 7.5 L/s[4] (10 to 15 cfm). Results of the DeltaQ test are shown in Figure 2.

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[3] The insulation was degraded according to the *Residential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for California (*California Energy Commission. 2005.*)*

[4] This range is due to test uncertainty.

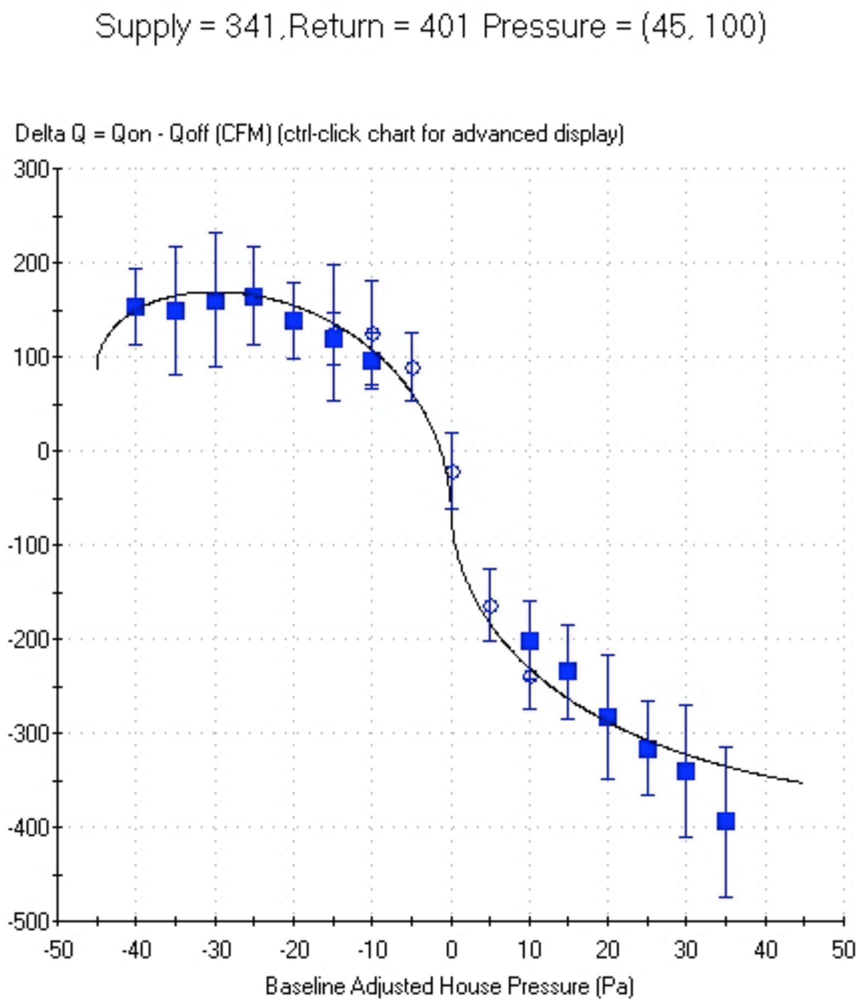

Figure 2. DeltaQ duct and envelope leakage test results

Controller installation and operation

The controller was installed into the test house and measurements made to determine the impact of the controller. The experiments lasted several weeks in the late summer of 2008. Data was collected on energy use, indoor and outdoor environmental conditions and ventilation performance.

Because the actual field test was only a few weeks long, a calibrated simulation model was used to extrapolate annual performance from the diagnostic and real-time measurements at the test site. The results include an analysis of both the field data and simulation results.

The ventilation fan was operated in three modes: ON, OFF, and under RIVEC control. Figure 3 shows the relative exposure, relative dose, total ventilation, and ventilation fan status when the ventilation fan was under RIVEC control. The relative dose and exposure were calculated using the measured fan flow rates. The relative dose used a 24 hour cycle time.

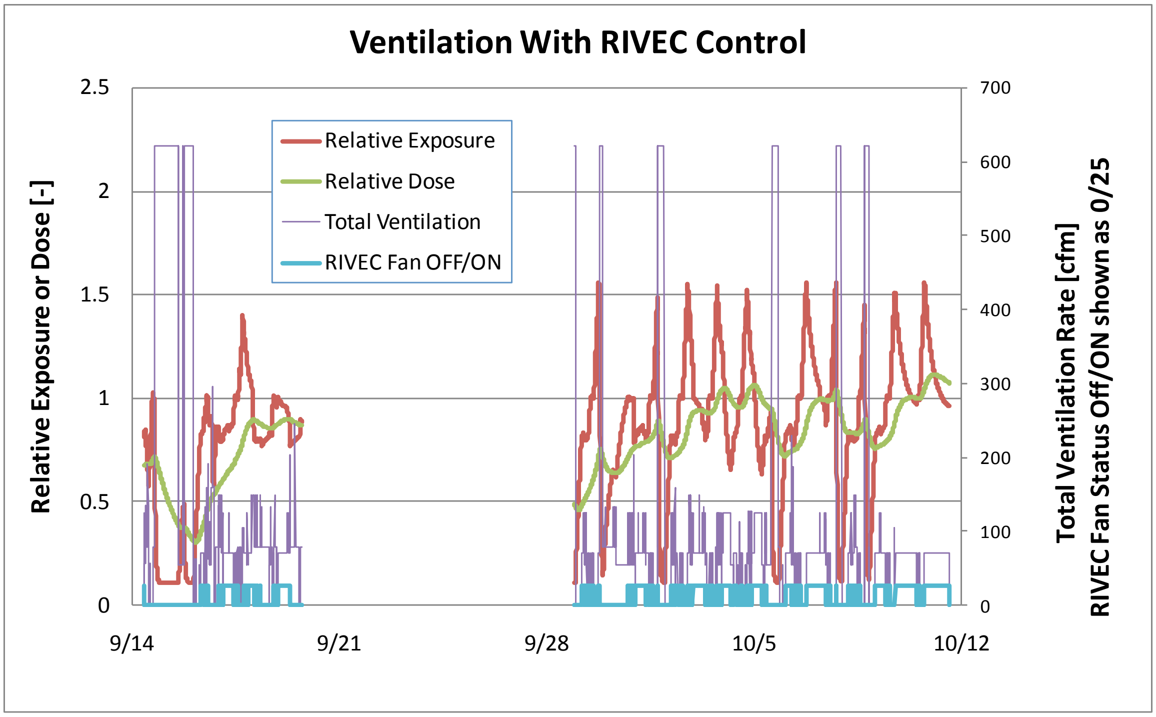

Figure 3. Ventilation Fan under RIVEC control.

The operation of the economizer, seen when the total ventilation is greater than 300 cfm, causes large reductions in relative exposure (down to 0.1 for the first long cycle) and relative dose. Because economizers are uncommon in residences and their operation can have a large impact on the exposure and dose, the analysis was done twice. First, including all the data, and second, excluding times within six hours after economizer operation. Figure 4 shows the same data as in Figure 3 but with these economizer hours removed.

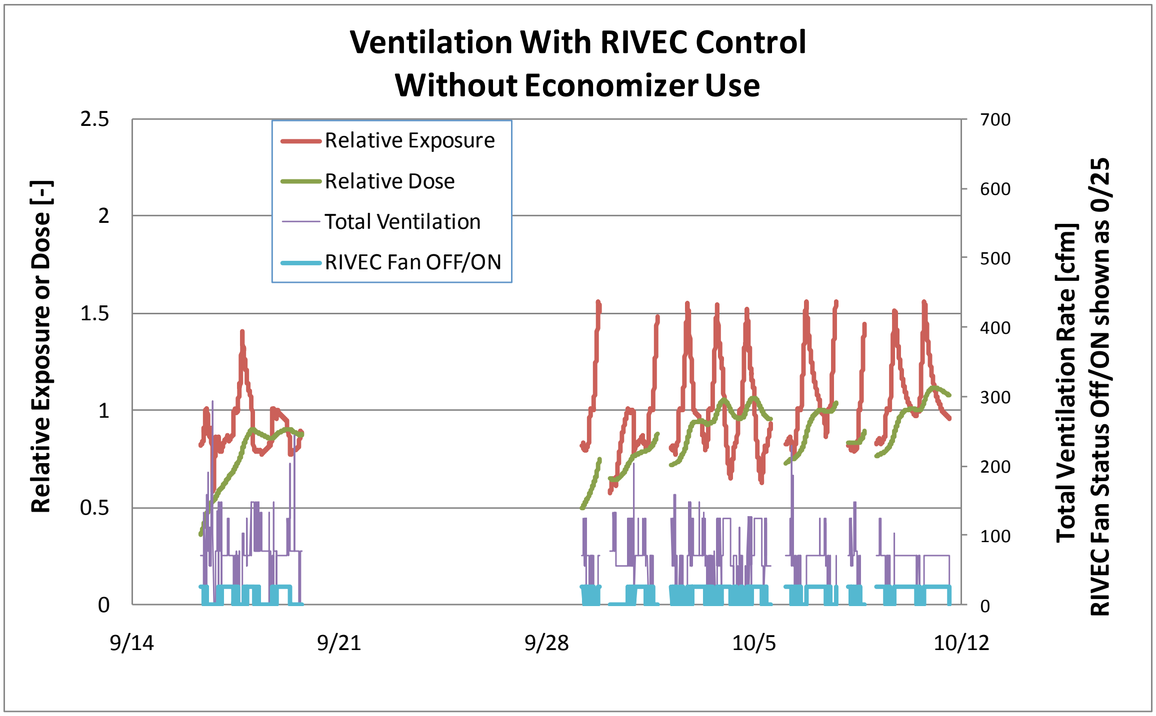

Figure 4. Ventilation Fan under RIVEC control with economizer operation removed.

Figure 5 focuses on three days which did not have economizer use where the RIVEC operation can be more easily seen.

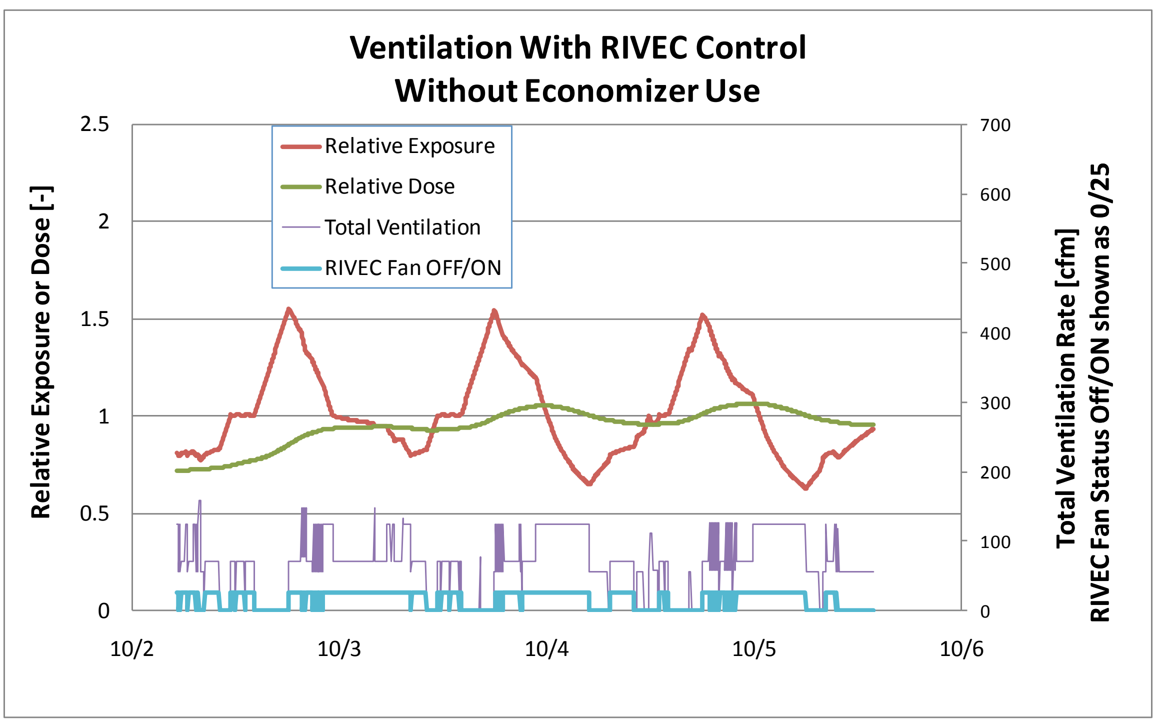

Figure 5. Three days without economizer use.

To see if economizer operation alone could be sufficient and to show the effect of not ventilating for several days, the controlled ventilation was forced OFF for six days and ON for two. Initially economizer use kept the relative dose under one, but without operating the economizer or ventilation fan the relative dose rose to about two.

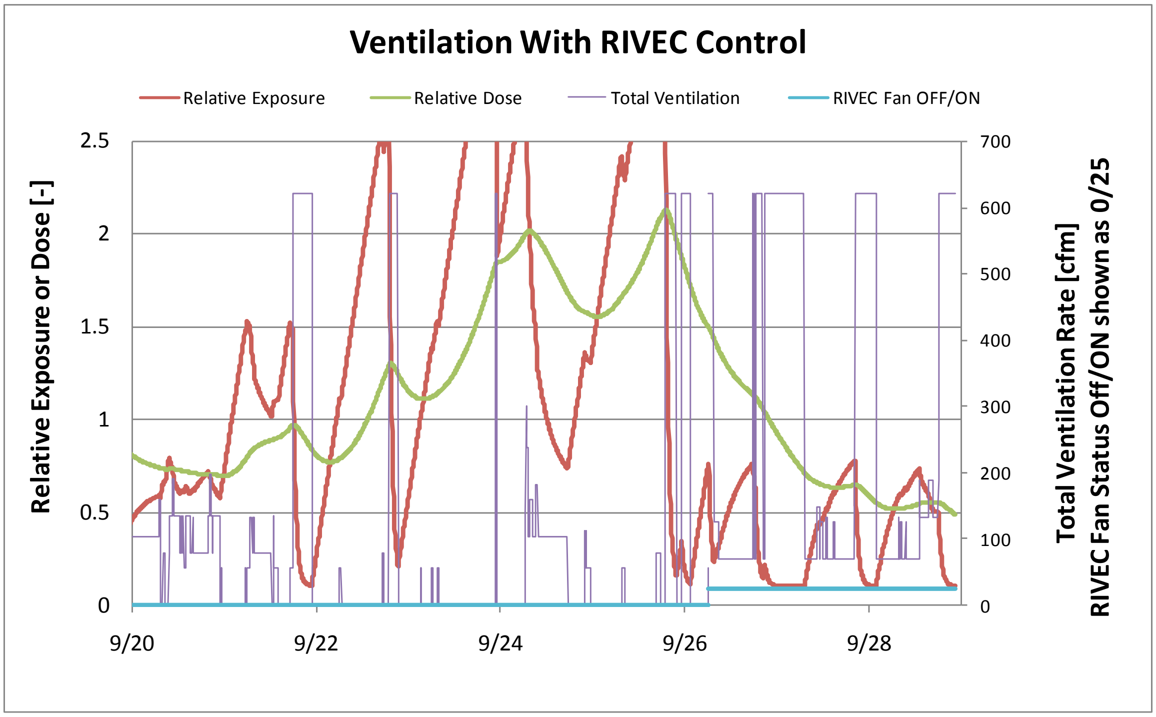

Figure 6. Days with 0% and 100% ventilation fan operation.

A summary of the ventilation rates, relative exposure and dose, outdoor temperature, and the percent on time of the ventilation fan was made for times including and excluding economizer operation. As shown in Table 1, the impact of economizer operation varies with the length of time it is on. For most cases its influence on the relative exposure and dose is small after it has been off for six hours or more.

Table 1. Measured RIVEC field test results

	All data			No Economizer operation for 6 hours		
	RIVEC control	Always ON	Always OFF	RIVEC control	Always ON	Always OFF
Total Airflow (cfm)	124	282	88	64	92	48
Average Relative Exposure	0.845	0.403	1.353	0.993	0.652	1.518
Average Relative Dose	0.802	0.779	1.258	0.853	0.698	1.215
Outdoor Temperature	60.6	70.4	63.9	60.1	82.3	65.2
% Ventilation Fan Operation	45	100	0	58	100	0

The ventilation fan is on about 50% of the time when RIVEC has control. During RIVEC control the average relative exposure and dose are less than one and seldom exceed 1.5 and 1 respectively while still maintaining the ventilation rates required (65 cfm). This demonstrates how the RIVEC device can reduce ventilation fan on time while still providing the ventilation required by ASHRAE 62.2.

Figure 7 shows the house energy use and daily maximum temperature during the test period. The house has a photovoltaic system that provides between 10 to 20 kWh each day at this time of the year. The remainder of the homes energy use, 30 to 50 kWh, is purchased from the local utility, Pacific Gas & Electric.

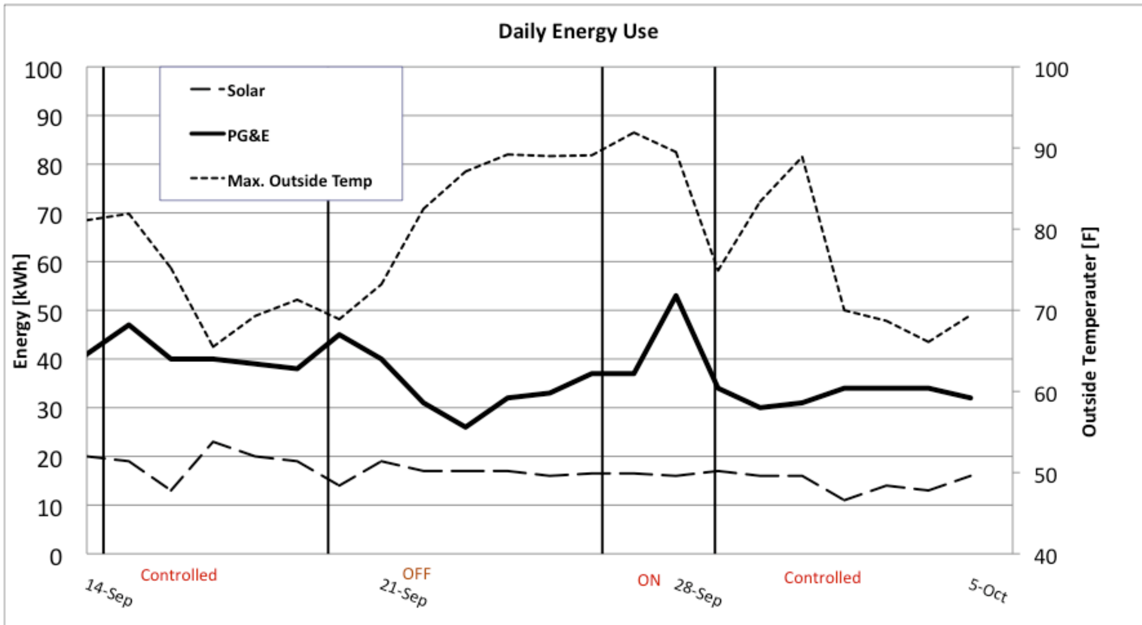

Figure 7: Moraga home energy use during the testing period.

To properly determine energy savings due to RIVEC operation, a full year's worth of data with continuous measurement of the infiltration rates and other occupant factors would be required. This is beyond the scope of the field study, therefore simulations were used to extrapolate the performance to a year in the following section.

2. Extrapolation of Test House Performance by Simulation

The test house in Moraga was simulated for a full year. Although geographically in Climate Zone 3, the weather in Moraga is more like Climate Zone 12 – so the CZ 12 weather data were used. Three simulations were performed: the first was of the house in normal operation, the second was with RIVEC controlling the whole house ventilation system, and the third was with no mechanical ventilation. Additional simulations were performed to examine the effect of other fan scheduling. The two fan scheduling options were: using the observed kitchen, bath and dryer schedules from the Moraga house (as recorded during the RIVEC field evaluation) and the standard schedule used for all the other simulations.

The RIVEC algorithm was integrated into the REGCAP simulation tool used in previous studies for the Energy Commission (Walker and Sherman (2006) and Sherman and Walker (2008)). This tool performs minute-by-minute ventilation, heat and moisture calculations that allow for the dynamic performance of buildings and HVAC components in both the house and the attic (where the HVAC equipment was located in the field test house and in all the simulations). The small timesteps are computationally and analytically intensive but allow for direct simulation of temporally complex ventilation controls, such as RIVEC. REGCAP combines a mass balance for air flows with a thermal model including the HVAC system and a moisture transport model. The air flow model allows individual (such as passive vents or flues) and distributed leaks (such as over a wall) to be placed on the building envelope. A rectangular floor plan was assumed and the envelope leaks were separated into leaks in each of the four walls, four floor level leaks and the ceiling. The flow through each leak was determined by the air flow characteristics of the leak (flow coefficient and pressure exponent) and the pressure across the leak. The pressure across the leak depended on both wind pressures and buoyancy pressures due to indoor-outdoor temperature differences. The mechanical ventilation systems were integrated into the mass balance as constant flow devices. The mass balance for the house and attic was solved by adjusting the internal pressures of the two zones (house and attic). Because the equations are highly non-linear, a simple pressure bisection technique was used to determine the attic and house interior pressures as this has proven to be an extremely robust solution technique. The thermal model in REGCAP used:

- overall UA values for the building envelope to determine heat transfer through the envelope of the house. House insulation levels and window performance were based on California Energy Code requirements (California Energy Commission 2005) and included degradation due to incorrect installation per the code requirements.
- solar gain through windows that depends on the solar heat gain coefficient and orientation. The solar part of the model used standardized calculations based on those in ASHRAE Fundamentals (ASHRAE 2005) together with measured solar radiation in the weather data.
- the mass flows derived by the air flow mass balance.
- the heat input or removed by the HVAC equipment including latent removal by air conditioning.
- internal gains based on California Energy Code requirements (California Energy Commission 2005).

A total of 16 heat transfer nodes were identified including air in the ducts, house, and attic, and used in a lumped heat capacity analysis.

The key issue with the use of this particular simulation tool is the ability to account for HVAC system, house and attic air flow, thermal and moisture transport interactions.

Other Simulation Input

The measured ceiling area and observed insulation levels in the attic were used to determine the ceiling heat transfer characteristics separately from the other portions of the envelope because this is required as a separate input for the simulations.

The eave height was measured to be 2.8 m.

The home is relatively well sheltered from the wind by neighboring homes and trees so the urban home wind shelter values used in the other simulations for this study were used, however the roof shelter was reduced from 1.0 to 0.7.

For the attic, its leakage was assumed to scale with surface area and assumed the same construction techniques as used in the other simulations in this study resulting in an attic leakage coefficient of 0.25 m^3/sPa^n. The soffit leakage was distributed with 35% in each of the long faces of the home, 10% in the short faces and 10% in the gables. Attic volume was estimated from dimensional measurements of the attic at 264 m^3. Roof pitch was measured to be 22 degrees (5/12) with a peak height of 5.8 m. The roof surface was asphalt shingle (used to determine radiation and thermal mass properties).

The air ducts were all R4 insulated flex. The return ducts were in the attic with a total length of 16 m (53 ft) and 40 cm (16 in.) diameter. The supply ducts were in the crawlspace and without a crawlspace zone in the model we needed to approximate the conduction losses from the supply ducts by setting the fraction outside to be one half. The effective surface area for the supply ducts was based on default values used in ASHRAE Standard 152, i.e., 27% of floor area. Halving this resulted in a supply duct surface area of 43 m^2 (460 ft^2) – equivalent to 15 m (147 ft) of eight inch diameter insulated duct.

The heating and cooling equipment was two separate units in the home that were combined into a single capacity and air flow system. The total cooling airflow was 0.964 m^3/s (2045 cfm) and heating air flow was 0.581 m^3/s (1231 cfm) (and power consumption at 2cfm/W of 1020 W and 615 W, respectively).

Total cooling capacity was 6.5 tons (78 kBtu/h or 22.9 kW) with an EER of 11, and the system was assumed to be fully charged.

Heating input capacity was taken from the furnace nameplates and was 147 kBtu/h (43 kW) with an assumed AFUE of 80% based on furnace age and type.

Ventilation Devices

The ventilation devices were simulated in two scenarios. The first was based on the actual operating pattern at the Moraga house that was observed in field evaluation of RIVEC. The second used the standard ventilation fan operation schedules as used for all the other simulations. The economizer operation was the same in both cases as the economizer control parameters for all the simulations were based on those observed at the Moraga House. In both cases the house had a continuous mechanical exhaust system operating that had an air flow of 71.5 cfm (0.0337 m^3/s). This is the minimum air flow required to meet ASHRAE Standard 62.2. This was assumed to be an efficient fan with a power consumption of 35 W.

Moraga House Schedule:

The home has three bathroom exhausts of 62 cfm, 55 cfm and 78 cfm for a total of 195 cfm (0.092 m^3/s). Power requirements for these fans were 0.9 cfm/W or 217 W with all three operating.

The bath fans operated for an hour every morning from 7:00 a.m. to 8:00 a.m. and half an hour every evening from 8:30 to 9:00 p.m.

The kitchen fan had an air flow rate of 104 cfm (49 L/s 0.049 m^3/s) and had a power consumption of 116 W. The kitchen fan operated for half an hour per day from 5 to 5:30 p.m.

The clothes dryer fan was assumed to be 150 cfm (75 L/s, 0.071m^3/s). The schedule for the dryer fan operated for five hours each weekend day from 11:00 a.m. until 4:00 p.m.

Standard Schedule:

The bath fans were assumed to operate for half an hour every morning from 7:30 a.m. to 8:00 a.m.

The kitchen fan operated for one hour per day from 5–6 p.m.

The schedule for the dryer fan assumed two days of laundry each week – each with three hours of continuous dryer operation from noon until 3:00 p.m.

Economizer

This house had an economizer with a measured air flow of 0.29 m^3/s (620 cfm) (and power consumption at 2 cfm/W of 310 W). The economizer operated in cooling mode when the outdoor temperature was 6°F or more below the indoor setpoint.

The RIVEC fan was sized to provide the ASHRAE 62.2 required mechanical ventilation for a 3400 ft2, 4 bedroom home of 71.5 cfm (0.0337 m^3/s). Using an energy efficient fan the power consumption was assumed to be 35W.

Moraga House Simulation Results

During the cooling season the economizer operation dominates the ventilation of the home. Its large airflows for several hours at a time repeated on an almost daily schedule lead to rapid reductions in relative exposure and low relative dose, as shown in Figures 8 and 9.

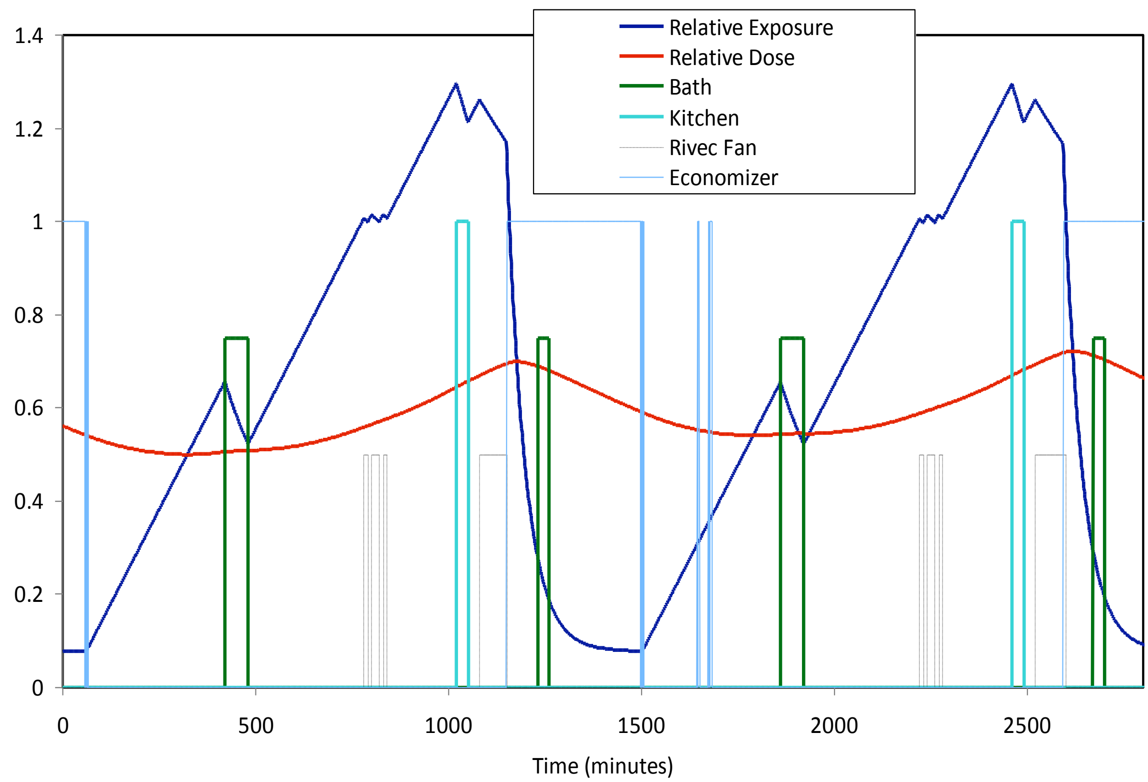

Figure 8. Moraga fan schedule RIVEC operation for cooling

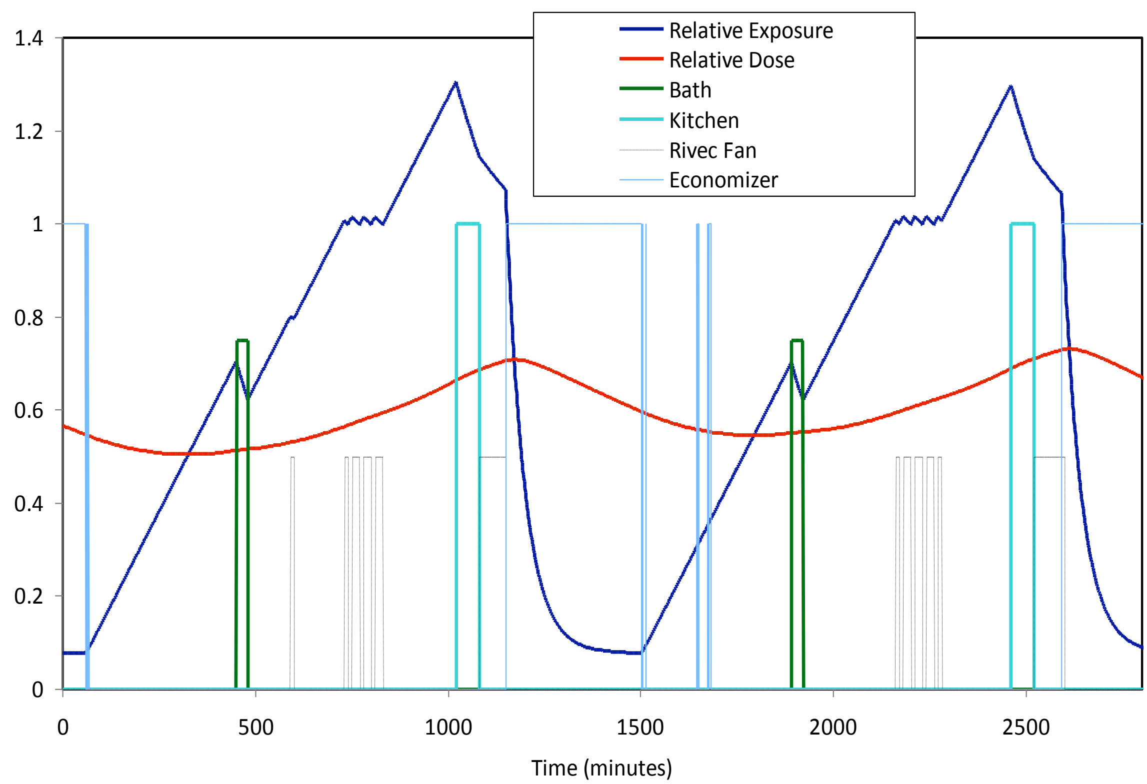

Figure 9. Standard fan schedule RIVEC operation for cooling in Moraga house

During the heating season there is no economizer operation and the relative exposure and dose are averaged close to unity over a multi-day period with diurnal cycles corresponding to the operation of kitchen and bath fans, together with the RIVEC controlled whole house system. This is illustrated in Figures 10 and 11.

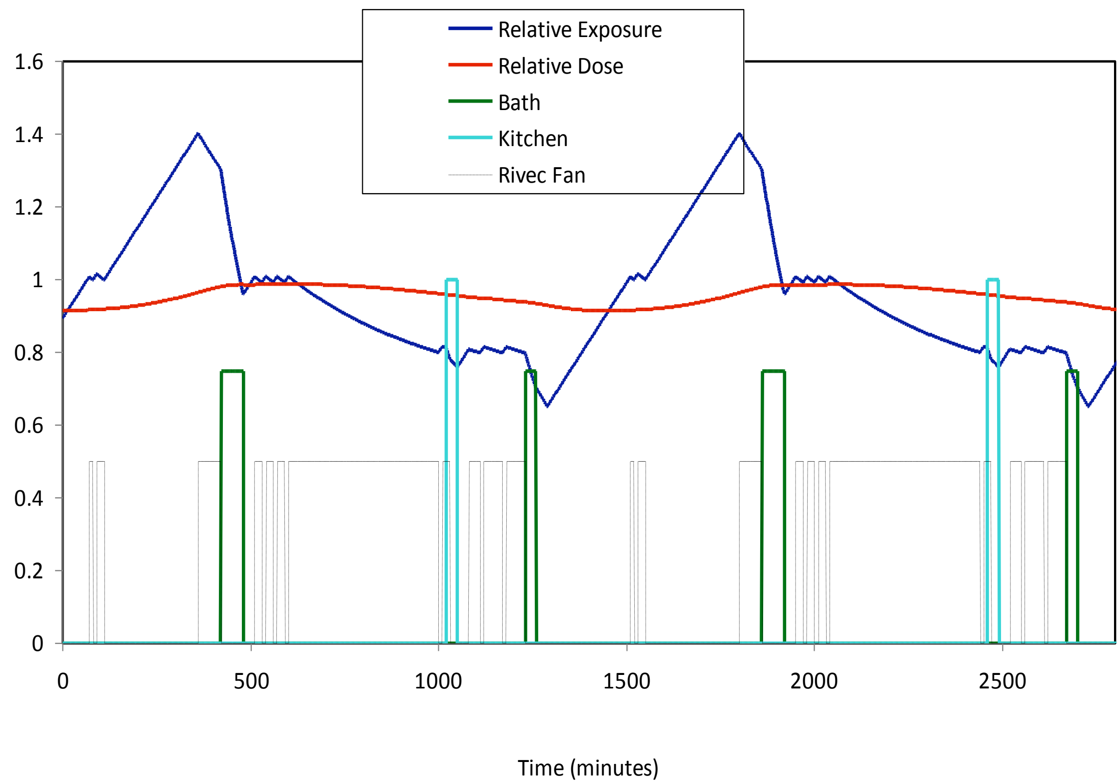

Figure 10. Moraga fan schedule RIVEC operation for heating

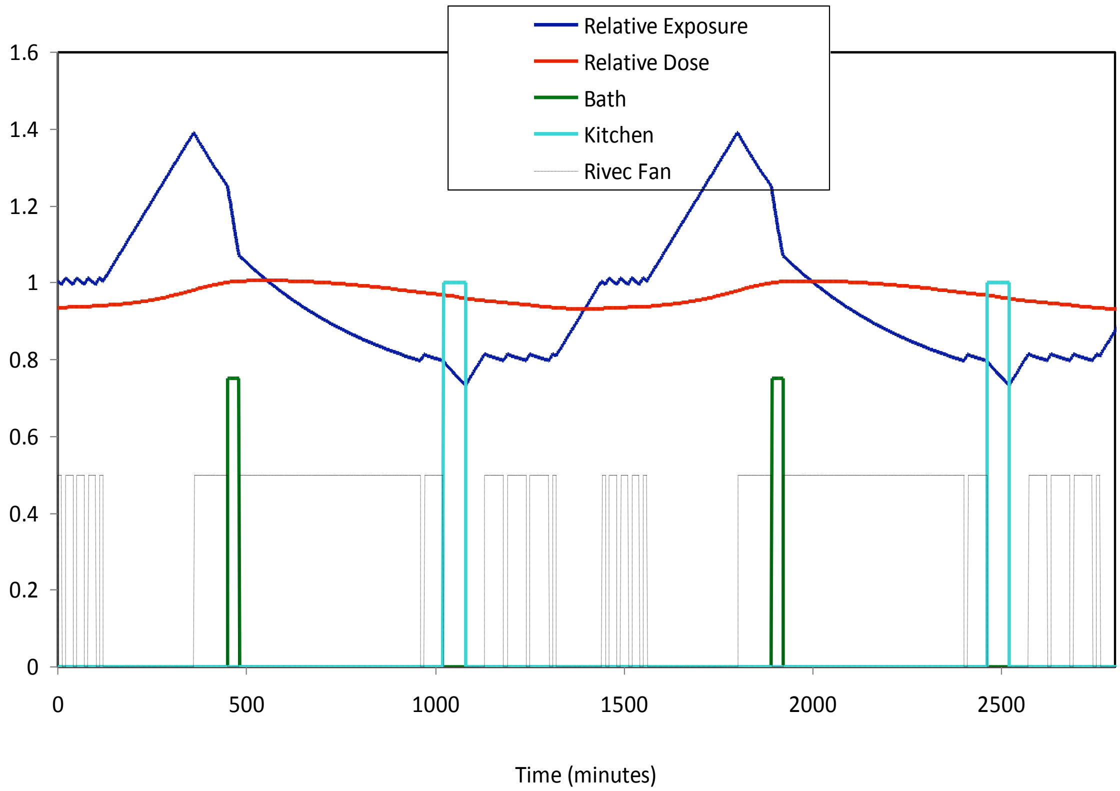

Figure11. Standard fan schedule RIVEC operation for heating in Moraga house

Looking at annual energy use and comparing the non-RIVEC and RIVEC vented cases to unvented the following figures (12-14) illustrate the increase in energy use. Most (>80%) of this energy increase is due to conditioning the ventilation air. Table 2 summarizes the changes in annual average air change rate relative to the unvented case showing the smaller increases in ventilation as a result of using the RIVEC controller.

Table 2. Increase in Air Change Rate (ACH) due to whole house mechanical ventilation

	RIVEC
Observed Moraga Venting Schedule	0.018
Standard Venting	0.022
	Non-RIVEC
Observed Moraga Venting Schedule	0.058
Standard Venting	0.056

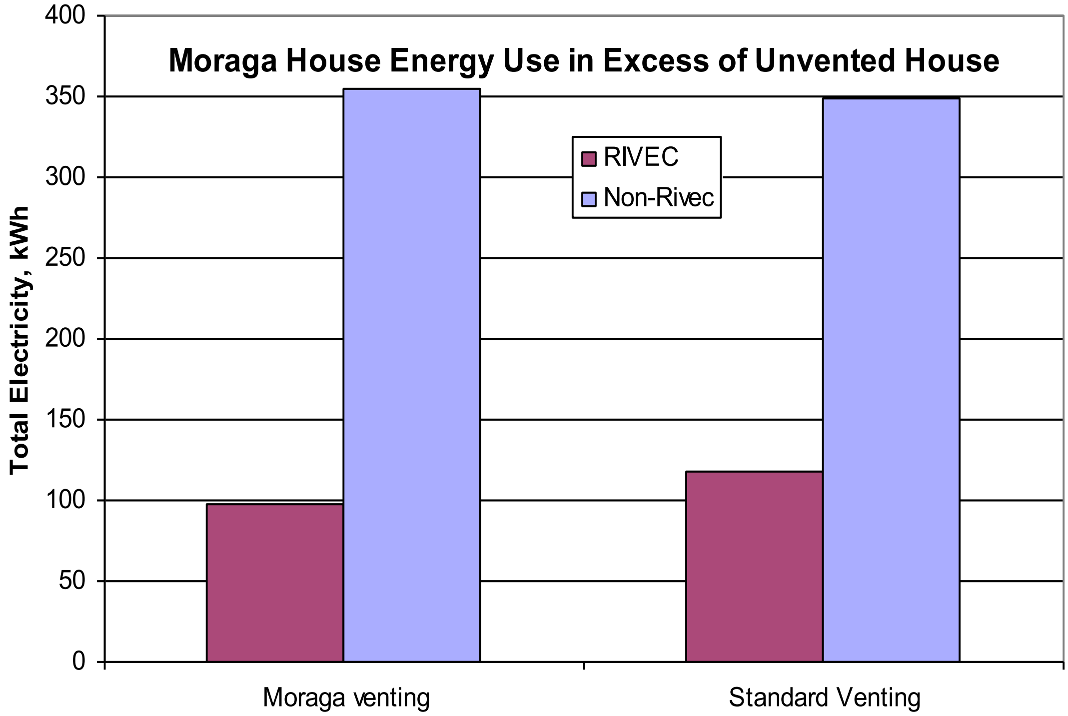

Figure 12. Simulated Electricity Use of RIVEC and non-RIVEC ventilated homes relative to a house with no continuous mechanical ventilation

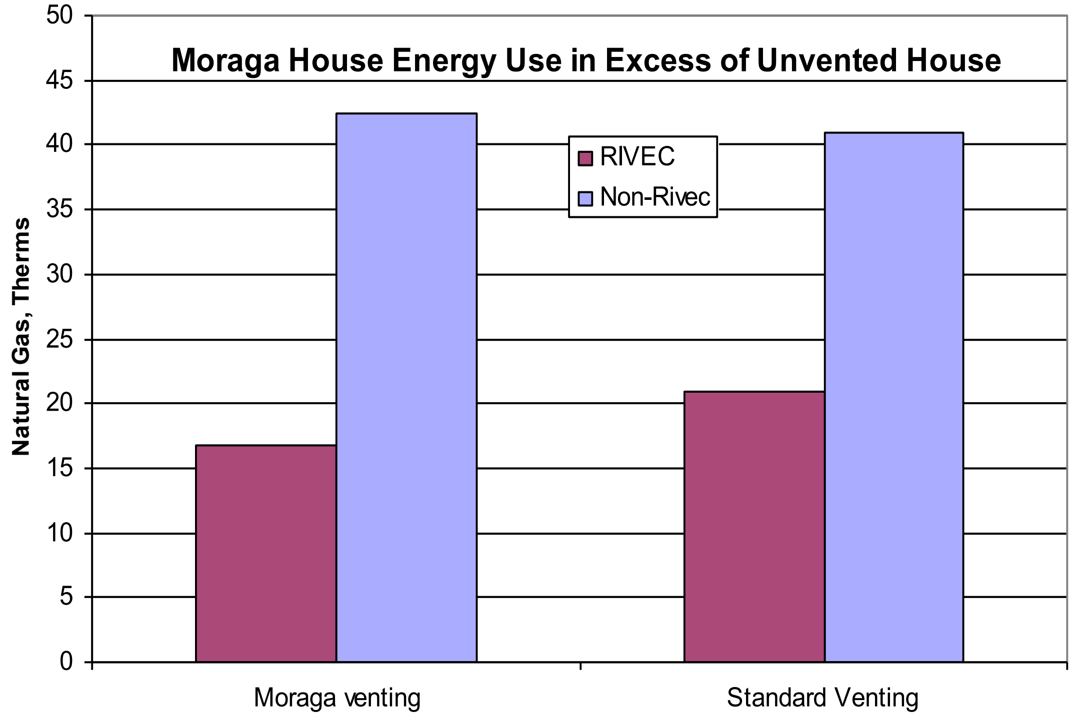

Figure 13. Simulated Natural Gas Use of RIVEC and non-RIVEC ventilated homes relative to a house with no continuous mechanical ventilation

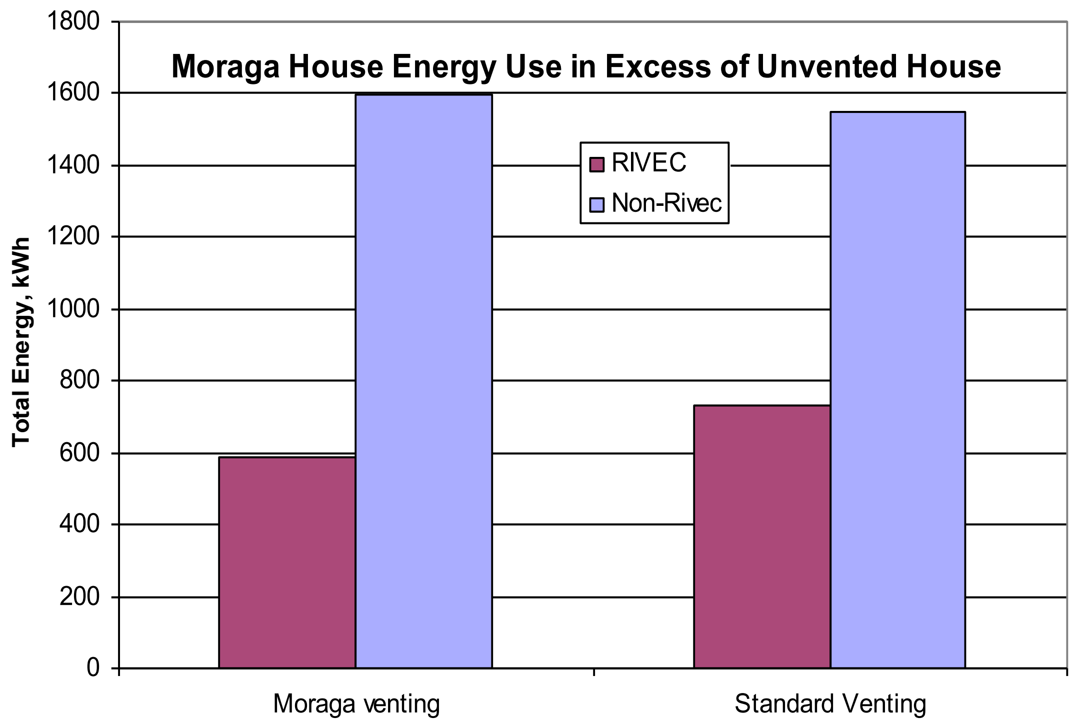

Figure 14. Simulated Total Energy Use of RIVEC and non-RIVEC ventilated homes relative to a house with no continuous mechanical ventilation.

Replotting these data of RIVEC savings relative to the Non-RIVEC mechanical ventilation (Figures 15-17) shows the expected impact of the RIVEC controller at this house. The additional bathroom ventilation relative to the standard assumptions observed at the Moraga house led to RIVEC turning off the whole house system more often. This resulted in greater savings using the observed mechanical ventilation schedule compared to the standard bathroom. The total RIVEC energy savings was about 1000 kWh for the Moraga field test home.

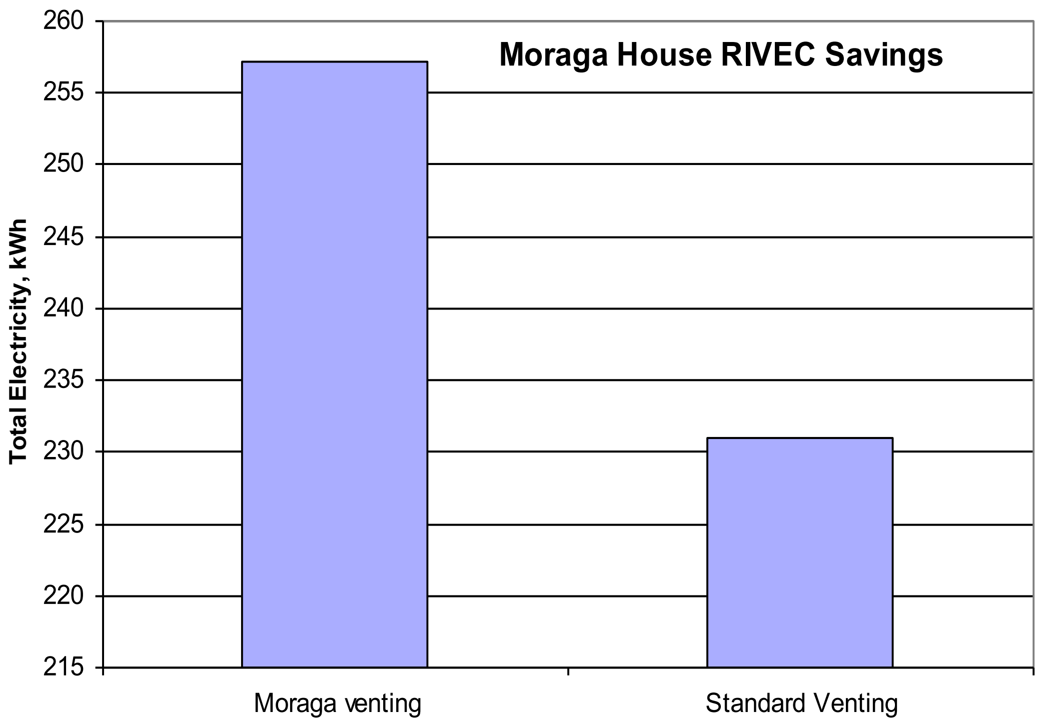

Figure 15. Simulated Electricity savings due to RIVEC operation for Moraga House.

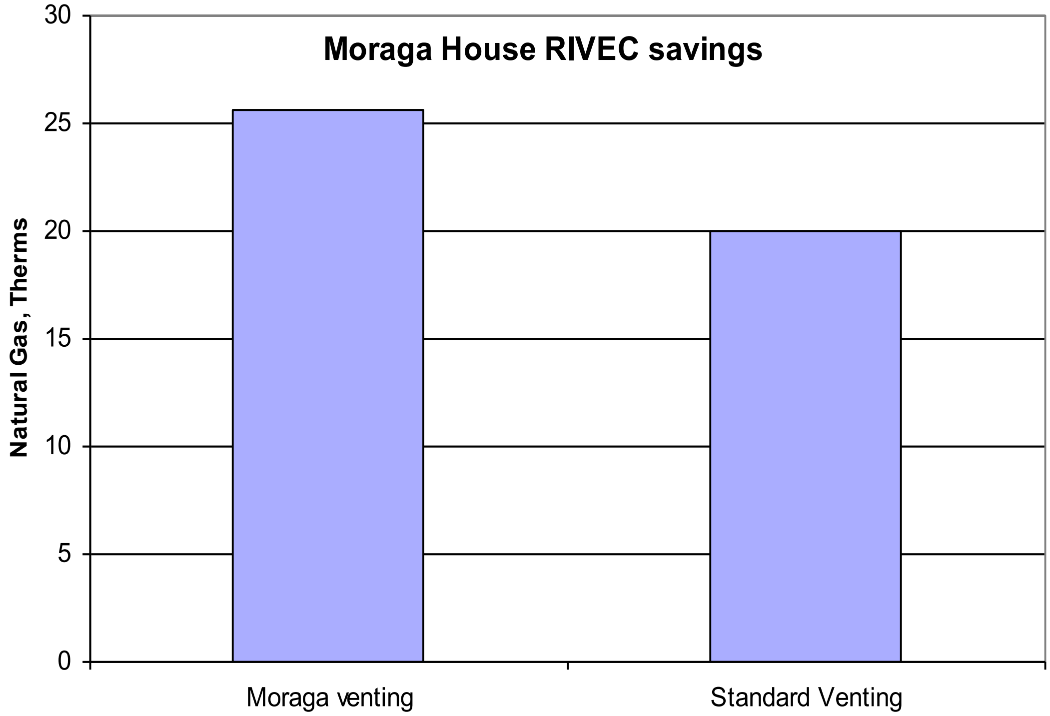

Figure 16. Simulated Natural Gas savings due to RIVEC operation for Moraga House.

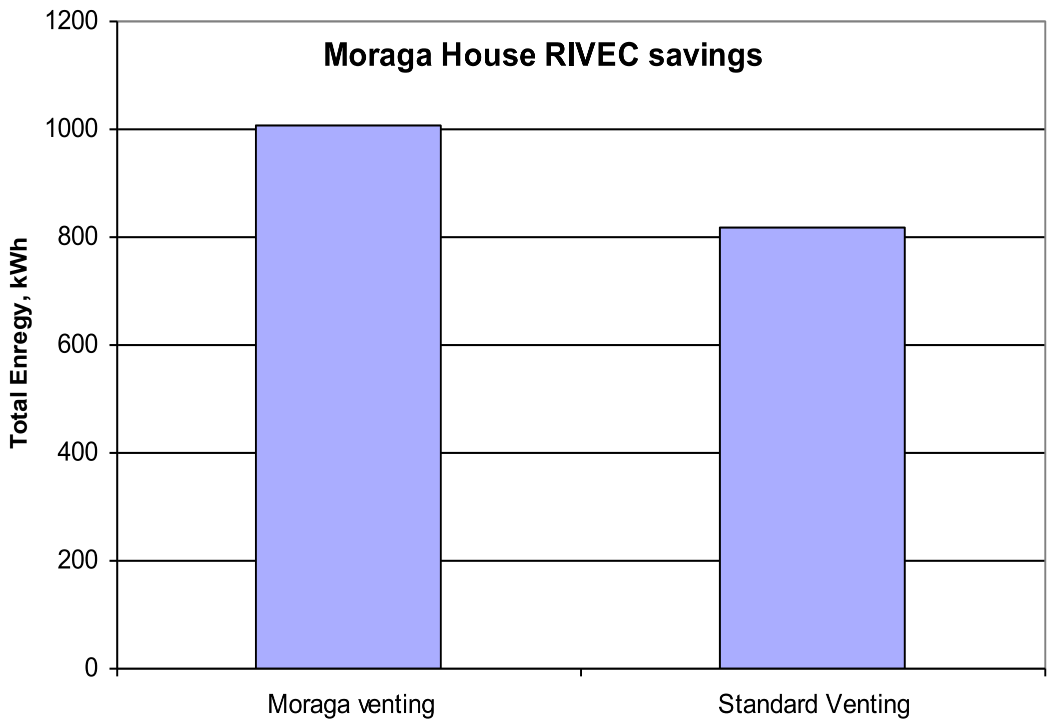

Figure 17. Simulated Total Energy savings due to RIVEC operation in Moraga house.

Fractional Runtime Summary

Table 3 summarizes the fractional runtime for the whole house fan. With no RIVEC controller the whole house fan would operate 525,600 minutes per year. The Moraga house shows fractional runtimes of 29% using the observed kitchen, bath and dryer fan operation and 36% using the standard approach. In both simulations an economizer operated in the summer months, and as shown in the other simulations it leads to significant reductions in whole house fan operation using RIVEC.

Table 3. Fractional runtime for RIVEC controlled whole house fans

Simulation		Number of minutes on	Fractional Runtime
12EISGMR	Moraga House with observed vent fan schedule	153700	0.29
12EISGTR	Moraga House with standard vent fan schedule	189510	0.36

Other Climate Simulations

In order to extend the results to a wider range of conditions, additional simulations were performed for a standardized home (based on the Title 24 prototype) in three California climate zones.

Climate

The study focuses on three climates based on the California State Energy Code (Title 24) climate zones: Zone 3 (Temperate), Zone 13 (Hot Central Valley where there is lots of new construction), Zone 16 (Cold). Table 4 summarizes the geographical data for these climates.

Table 4. California Climate Zone Summary

Climate Zone	City	Latitude	Longitude	Elevation (ft)
3	Oakland	37.7	122.2	6
13	Fresno	36.8	119.7	328
16	Mt. Shasta	41.3	122.3	3544

Weather

Weather data were taken from Title 24 compliance hourly data files converted to minute-by-minute format by linear interpolation. The simulations also used location data (altitude and latitude) in solar and air density calculations. The required weather data for the simulations were as follows:

- Direct solar radiation (W/m^2)
- Total horizontal solar radiation (W/m^2)
- Outdoor air dry-bulb temperature(°C)
- Outdoor air humidity ratio
- Wind speed (meters per second [m/s])
- Wind direction (degrees)
- Barometric pressure (kPa)
- Cloud cover index

Building

The building was based on the 1761 ft^2 prototype Title 24 home. The house and duct insulation used to determine the non-ventilation building load, and duct system performance varied by climate as shown in Table 5[5]. The insulation was degraded

[5] Based on CA T24 2005 Package D requirements including degradation factors.

according to the *Residential Alternative Calculation Method (ACM) Approval Manual for the 2005 Building Energy Efficiency Standards for California*[6].

Table 5. House insulation levels

Climate Zone	Ceiling			Wall		Ducts outside conditioned space
		Heating Degraded	Cooling Degraded		Degraded	
3	R30	18.8	26.1	R13	10.9	R6
13	R38	21.6	31.9	R19	10.9	R6
16	R38	21.6	31.9	R21	17.6	R8

The exterior surface area for wall insulation scaled with floor area and number of stories. Wall-to-floor area ratios and window -to-floor area ratios were developed from measured data from several thousand new homes[7] and from the simplified box prototype C in the ACM manual. The wall area was assumed to be 1.54 times the floor area for a two-story home and 1.22 times the floor area for a one-story home. Window area was 20% of floor area with windows equally distributed on the four exterior walls. The solar heat gain coefficient (SHGC) varied by climate zone between 0.4 and 0.65. Values specified in ACM Table 151-C, p.133 were used. In climate zones where a minimum SHGC was not required, ACM Tables 116-A and 116-B, p.56 were used. The required U-value (the measure of air-to-air heat transmission due to thermal conductance and the difference in indoor and outdoor temperatures) was taken from ACM Table 116-A, and the SHGC corresponding to the same window from table 116-B was used. Clear glazing was assumed as was an exterior shading of 50%. For the envelope leakage, an SLA of 4 will be used (this was the recommended value from California Building experts for a previous CEC ventilation study by the authors).

Table 6. Envelope leakage

Floor Area (ft^2)	SLA	ELA4 (in^2)	$m^3/(sPa^n)$	cfm/Pa^n
1761	4	101	0.067	143

Heating and Cooling Equipment Sizing

The equipment capacity was based on the results of a field survey of 60 new California houses performed as part of another PIER study (Wilcox (2006)). The resulting heating and cooling capacities are generally greater than those estimated using sizing calculations such as ACCA Manual J/S procedures. In some cases the cooling capacity determines the heating capacity due to the limited furnace packaging alternatives that are commercially available. Primarily this is an issue of furnace blower motor operating

[6] California Energy Commission. 2005.

[7] Based on BSC/Building America data.

ranges that restrict the differences in heating and cooling capacities that can be serviced by an individual blower.

The heating will be supplied by an 80% annual fuel utilization efficiency (AFUE) natural gas furnace. For cooling, a seasonal energy efficiency ratio (SEER) 13 split-system air conditioner with a thermostatic expansion valve (TXV) refrigerant flow control was used. The duct leakage to outside will be 6%, split with 3% supply leakage and 3% return leakage.

Table 7. Heating and Cooling System Sizing

Climate Zone	Heating Capacity (KBtu/h)	Cooling Capacity (Tons)	Heating Blower Power (W)	Cooling (and Ventilating) Blower Power (W)
3	84	1.5	563	300
13	103	4	689	800
16	147	3.5	983	700

Determination of heating or cooling operation was based on the Title 24 seven-day running average technique. When the seven-day running average outdoor temperature was greater than 60°F, cooling was assumed, and when it was less than 60°F, heating was assumed. However, in most climates this resulted in multiple switches between heating and cooling, which was unrealistic. Therefore, for each climate zone (CZ), one day was selected for the heating to cooling mode switch and one day for the cooling to heating mode switch, based on the seven-day running average technique. A list of the switching days is given in Table 8.

Table 8. Days to switch heating and cooling modes

CZ	Day of year to switch to cooling	Day of year to switch to heating
3	152	283
13	103	300
16	160	247

Operation of the heating and cooling equipment used the following set-up and set-back thermostat settings taken from the ACM and shown in Table 9.

Table 9. Thermostat settings for ventilation simulations (°F)

Hour	Heating	Cooling
1	65	78
2	65	78
3	65	78
4	65	78
5	65	78
6	65	78
7	65	78
8	68	83
9	68	83
10	68	83
11	68	83
12	68	83
13	68	83
14	68	82
15	68	81
16	68	80
17	68	79
18	68	78
19	68	78
20	68	78
21	68	78
22	68	78
23	68	78
24	65	78

Source Control

Intermittent bathroom fans operate for half an hour every morning from 7:30 a.m. to 8:00 a.m. These bathroom fans were sized to meet the ASHRAE 62.2 requirements for intermittent bathroom fans. From Table 5.1 in ASHRAE 62.2, this is 50 cfm (25 liters per second [L/s]) per bathroom. For houses with multiple bathrooms, the bathroom fans are assumed to operate at the same time, so the 1761 ft^2 house had a total of 100 cfm (50 L/s). Power requirements for these fans were 0.9 cfm/W based on California field survey data (Chitwood 2005 – personal communication), i.e., 55W for each 50 cfm fan).

Similarly, all simulations had kitchen fan operation. The kitchen fans operate for one hour per day from 5–6 p.m. These kitchen fans were sized to meet the ASHRAE 62.2 requirements for intermittent kitchen fans. From Table 5.1 in ASHRAE 62.2, this was 100 cfm (50 L/s). Unfortunately, very few of the kitchen fans in the HVI directory had power consumption information. The smallest of those that do [Ventamatic Nuvent RH160] was selected for these simulations. This fan had a flow rate of 160 cfm, and used 99 W.

RIVEC will detect if these fans are being operated and include these exogenous flows in the calculations of relative dose and exposure.

Clothes dryer fans are 150 cfm (75 L/s, 0.071m^3/s) exhaust fans. The schedule for the dryer fan will assume two days of laundry each week – each with three hours of continuous dryer operation from noon until 3:00 p.m.

Alternative Ventilation Strategies with RIVEC

The ASHRAE 62.2 requirement for a 1761 ft^2 home with 3 bedrooms (4 occupants) is 48 cfm. The system connected to RIVEC will be sized to at least 25% above that rate.

Intermittent Exhaust

The system consisted of a bathroom fan that is on for 20 hours and off for 4 hours during peak (3–7 p.m. for cooling and 1–5:00 a.m. for heating). The relationships given in an *ASHRAE Transactions* article (Sherman 2005) and ASHRAE 62.2 show that intermittently under-ventilating for 4 hours out of 24 (given the background natural infiltration and extra 25 cfm capacity of the continuous exhaust minimum flow required by 62.2) yielded acceptable, effective ventilation rates that met 62.2 requirements. *The ASHRAE 62.2 requirement for a 1761 ft^2 home with 3 bedrooms (4 occupants) is 48 cfm. Sized to operate 20 out of 24 hours this requires 58 cfm. This can be met with a 24.3 W Panasonic FV-08VF2 (power consumption and flow data are from HVI directory).*

Continuous Exhaust

The continuous exhaust meets the ASHRAE requirements of 48 cfm (0.0226 m^3/s) with a Panasonic FV-07VFL1 (at 0.25 in. water) using 19.1 W.

The RIVEC system will use a fan upsized by 25% consistent with ASHRAE 62.2 requirements for a fan that is on for 20 hours and off for 4 hours. RIVEC will control this fan to be off from 3–7 p.m. for cooling and 1–5:00 a.m. for heating. *Sized to operate 20 out of 24 hours this requires 60 cfm (0.0283 m^3/s). This can be met with a Panasonic FV08VF2 using 24.3 W.*

HRV

The HRV will be operated to meet ASHRAE 62.2 requirements. Most common HRVs have air flow rates that exceed these requirements and therefore only operate for a fraction of each hour. The selected HRV has an air flow of 138 cfm. To meet the ASHRAE 62.2 minimum requirement of 48 cfm for this house this requires only 21 minutes per hour of operation. The HRV will be simulated for the cold climate (CZ 16) only. The HVI directory listed recovery efficiencies were applied to the air flow through the HRV when calculating the energy use. For these simulations, the apparent sensible effectiveness (ASE) was used to determine the temperature of air supplied to the space ($T_{tospace}$). It was assumed that the HRV has its own duct system that does not leak and is located entirely within the conditioned envelope of the house.

$$ASE = \frac{T_{out} - T_{tospace}}{T_{out} - T_{fromspace}} \quad \textbf{(9)}$$

The HRV selected from the HVI directory [Broan Guardian HRV 100H] was assumed to be installed correctly and operating at the rated pressure drop. With these assumptions, this HRV uses 124 W at 138 cfm [0.0652 m^3/s] net airflow at the 0.44 inches of water [110 Pa] external static pressure of the standard HVI rating point and has:

- Apparent sensible effectiveness = 70%
- Sensible recovery efficiency = 62%

The HRV will operate interlocked with the furnace fan so that the furnace fan operates whenever the HRV is operating. RIVEC bypasses the standard timer and provides its own timer, clock and furnace operation tracker.

CFI and Continuous Exhaust

A CFI supply uses the furnace blower to intentionally draw outdoor air through a duct into the return and distribute it throughout the house using the heating/cooling supply ducts. The outdoor air duct was only open to outdoors during furnace blower operation and has a damper that closes when the furnace blower is off. This damper was assumed to have zero leakage when closed. The flow through the outside air duct is sized to meet 62.2 (i.e., 48 cfm) during operation. The CFI automatically operates for a minimum of 20 minutes out of the hour. The CFI supplements a 48 cfm continuous exhaust fan that meets the ASHRAE requirement. For RIVEC, the exhaust fan will be 25% oversized (as in case 1) to allow for four hours of non-operation per day.

Continuous Supply

For continuous supply, the supply air is mixed with indoor air for tempering purposes. A mixing ratio of 3:1 was used for indoor to supply air. The supply fan will therefore be sized to be four times the ASHRAE 62.2, i.e., 192 cfm. A Greentek PTF 150 in-line fan provides this flow at a power consumption of 81 W (at 150 Pa pressure difference), of which 13 W is air power and 68W is heat (this motor heat is added to the building energy balance).

Economizer

When the economizer operates RIVEC will take into account the economizer operation on indoor air quality and delay use of the whole-house ventilation system based on the calculated relative dose and exposure.

An economizer provides cooling and ventilates incidentally. Therefore the economizer will be used only in the cooling climate zone 13. The economizer will be modeled as a large supply fan with the same air flow rate and power consumption as the forced air system blower. The economizer will operate when the HVAC system is in cooling mode when the outdoor temperature is 6°F or more below the indoor setpoint. A large hole will opened (in the ceiling) for pressure relief. The hole will be sized to result in approximately 2Pa of house pressurization, i.e., c= 0.311 m^3/sPa^n or roughly 0.5 m^2.

When the economizer operates, the CFI system will be turned off in the simulations. In a real installation it is more likely that the CFI damper will continue to operate, however, this will not significantly change the system air flows because during economizer operation, the system is already using 100% outdoor air.

Simulation Output

The simulation output was recorded as minute-by-minute values of: ventilation air flow, fan operation, energy consumption (disaggregated by ventilation fan power (so we can track things like blower operation for CFI and HRV during heating/cooling and ventilating), heating, cooling) indoor temperature and humidity conditions, predicted relative dose and exposure.

Simulation Comparisons

There were three levels of simulation:

- The first level was for a house that did not meet the 62.2 requirements for mechanical ventilation. This house still had the intermittent kitchen and bathroom fans. This is the base case that we will compare the others to.
- The second level was for a house that met 62.2 requirements using the various mechanical ventilation systems.
- The third level was for houses that utilized a RIVEC controller for the 62.2 mechanical ventilation systems.

Table 10. Baseline Simulations

File Name	Climate Zone	62.2 Ventilation System	Other Fans	Reference for:
03EISG1N	3	None	Kitchen Fan Bath Fan	03EISG0 03EISG1 03EISG1R 03EISG4 03EISG4R
03EISG3N	3	None	Kitchen Fan Bath Fan CFIS	03EISG3 03EISG3R
03EISG5N	3	None	Kitchen Fan Bath Fan Economizer	03EISG5 03EISG5R
13EISG1N	13	None	Kitchen Fan Bath Fan	13EISG0 13EISG1 13EISG1R 13EISG4 13EISG4R
13EISG3N	13	None	Kitchen Fan Bath Fan CFIS	13EISG3 13EISG3R
13EISG5N	13	None	Kitchen Fan Bath Fan Economizer	13EISG5 13EISG5R
16EISG1N	16	None	Kitchen Fan Bath Fan	16EISG0 16EISG1 16EISG1R 16EISG2 16EISG2R 16EISG4 16EISG4R
16EISG3N	16	None	Kitchen Fan Bath Fan CFIS	16EISG3 16EISG3R

Table 11. Normal 62.2 Systems

File Name	Climate Zone	62.2 Ventilation System	Other Fans
03EISG0	3	Intermittent Exhaust	Kitchen Fan Bath Fan & Dryer
03EISG1	3	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer
03EISG3	3	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer CFIS
03EISG4	3	Continuous Supply	Kitchen Fan Bath Fan & Dryer
03EISG5	3	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer Economizer
13EISG0	13	Intermittent Exhaust	Kitchen Fan Bath Fan & Dryer
13EISG1	13	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer
13EISG3	13	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer CFIS
13EISG4	13	Continuous Supply	Kitchen Fan Bath Fan & Dryer
13EISG5	13	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer Economizer
16EISG0	16	Intermittent Exhaust	Kitchen Fan Bath Fan & Dryer
16EISG1	16	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer
16EISG2	16	HRV	Kitchen Fan Bath Fan & Dryer
16EISG3	16	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer CFIS
16EISG4	16	Continuous Supply	Kitchen Fan Bath Fan & Dryer

Table 12. RIVEC 62.2 Systems

File Name	Climate Zone	62.2 Ventilation System controlled by RIVEC	Other Fans
03EISG1R	3	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer
03EISG3R	3	Continuous Exhaust	Kitchen Fan Bath Fan & Dryer CFIS
03EISG4R	3	Continuous Supply	Kitchen Fan Bath Fan& Dryer
03EISG5R	3	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer Economizer
13EISG1R	13	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer
13EISG3R	13	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer CFIS
13EISG4R	13	Continuous Supply	Kitchen Fan Bath Fan& Dryer
13EISG5R	13	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer Economizer
16EISG1R	16	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer
16EISG2R	16	HRV	Kitchen Fan Bath Fan& Dryer
16EISG3R	16	Continuous Exhaust	Kitchen Fan Bath Fan& Dryer CFIS
16EISG4R	16	Continuous Supply	Kitchen Fan Bath Fan& Dryer

Simulation Results

Figure 18 illustrates the simulated operation of the fans and the resulting RIVEC fan control. Figure 18 is for two of days in winter and shows how the RIVEC fan is turned off for four hours each day and at other times corresponding to low relative dose or exposure. For heating mode, RIVEC is set to shut-off the ventilation during the most expensive 4-hr period of the day to ventilate—pre-dawn. After that period RIVEC keeps the ventilation system operating to compensate and then once it has, it cycles as needed. The corresponding exposure and dose are also shown in this figure. The exposure and dose calculations assume a constant pollutant emission rate and are normalized relative to the minimum air flow requirements of ASHRAE Standard 62.2. These results show that turning off the ventilation system using RIVEC retains the same relative dose as a non-RIVEC controlled ASHRAE 62.2 compliant system. Therefore, RIVEC maintains acceptable indoor air quality as defined by ASHRAE 62.2.

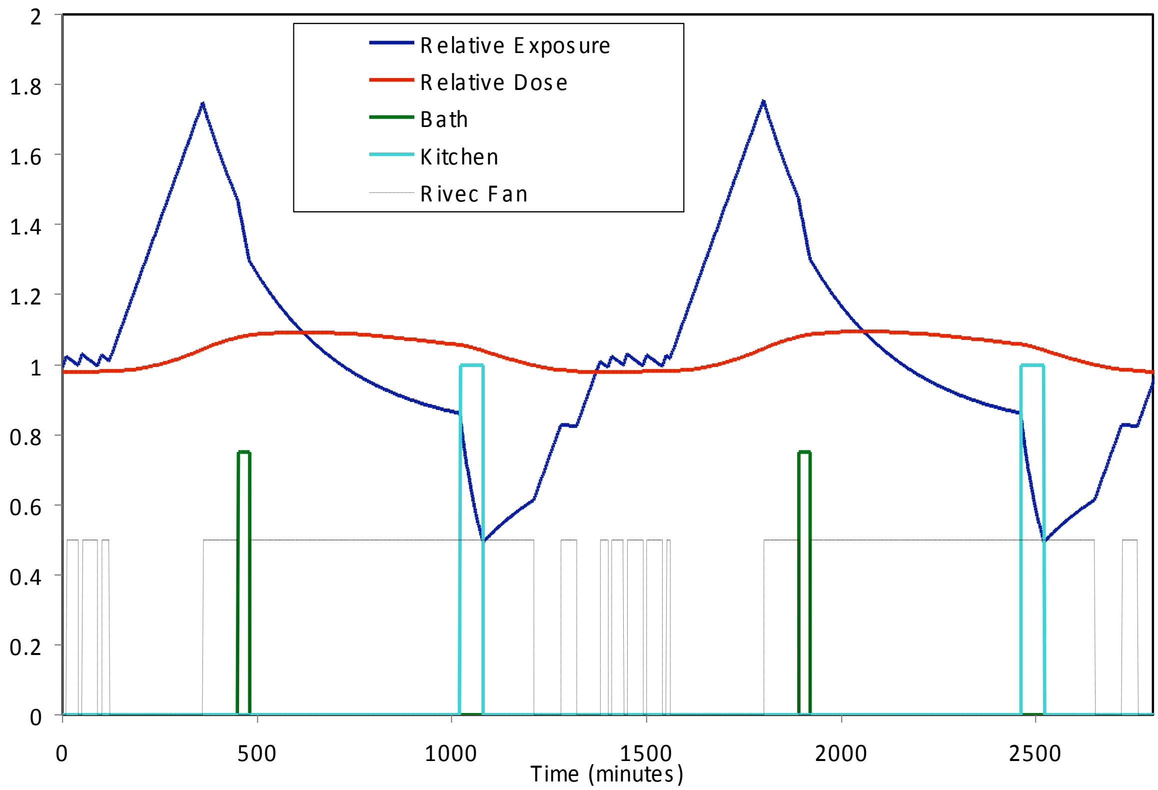

Figure 18 Illustration of RIVEC fan operation (CZ3 heating)

Figure 19 shows how RIVEC responds to the cycling behavior of an HRV. The RIVEC algorithms act to shut off the RIVEC controlled fan when the HRV is on, as well as when other fans operate and during the nighttime "off" period. Figures 20-25 illustrate RIVEC operation for other systems.

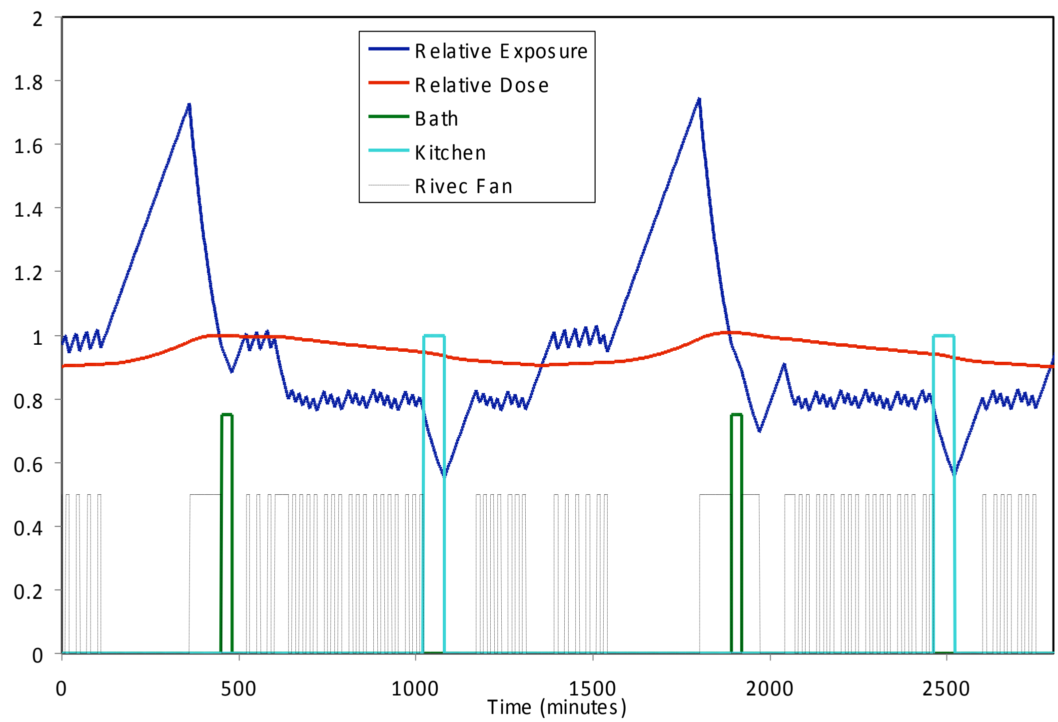

Figure 19. Illustration of RIVEC operation for a house with an HRV

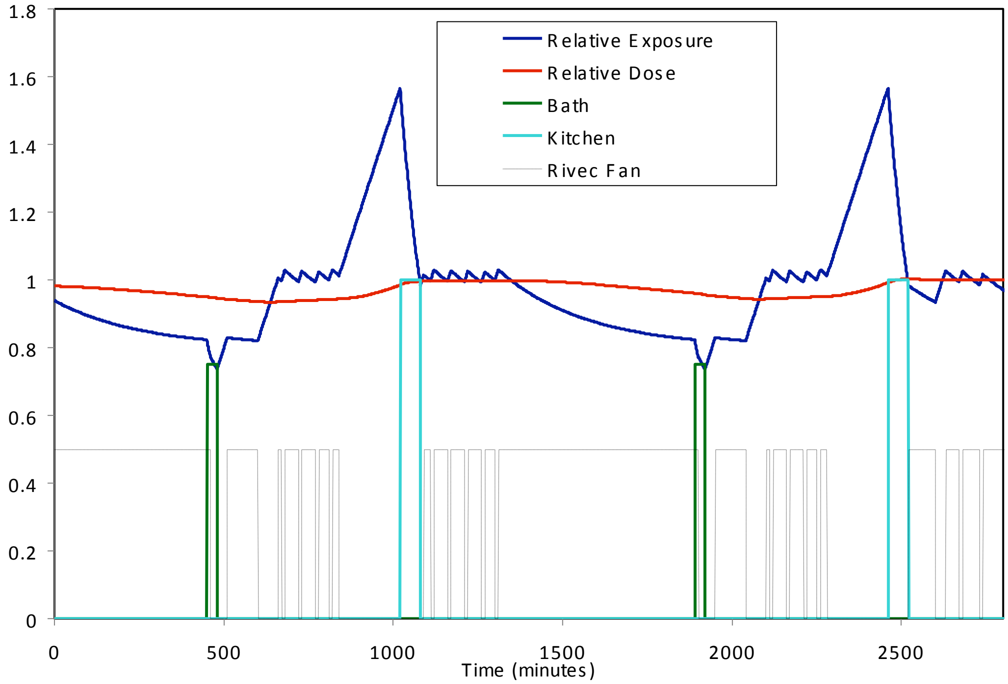

Figure 20. RIVEC operation for continuous exhaust in CZ3 in cooling season

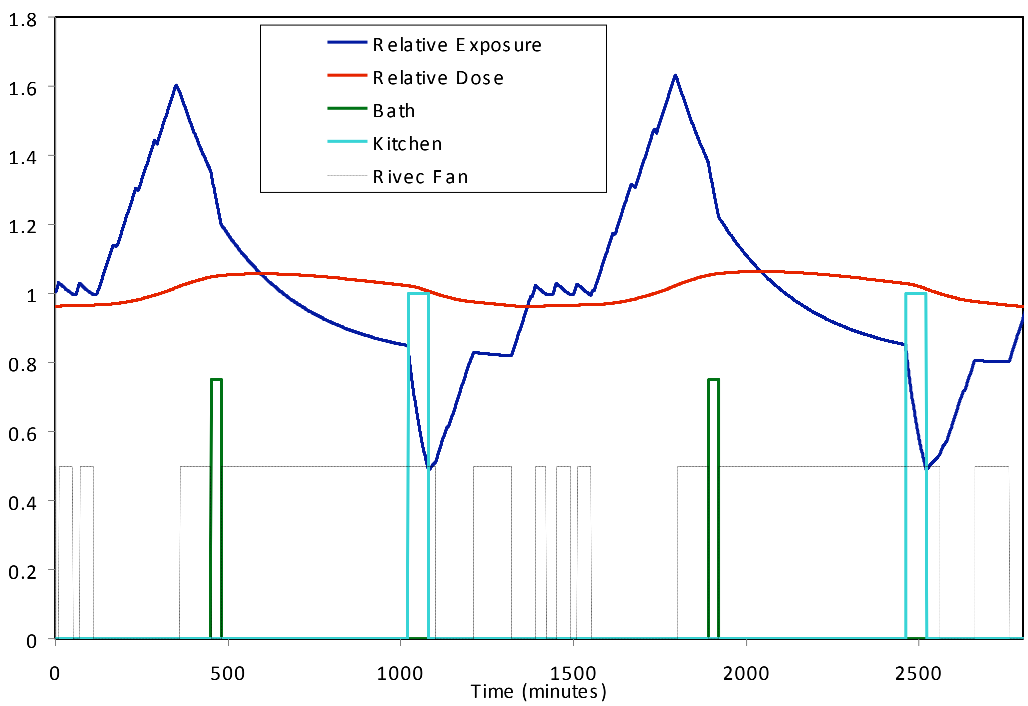

Figure 21. RIVEC operation for continuous exhaust + CFIS in CZ3 in heating season

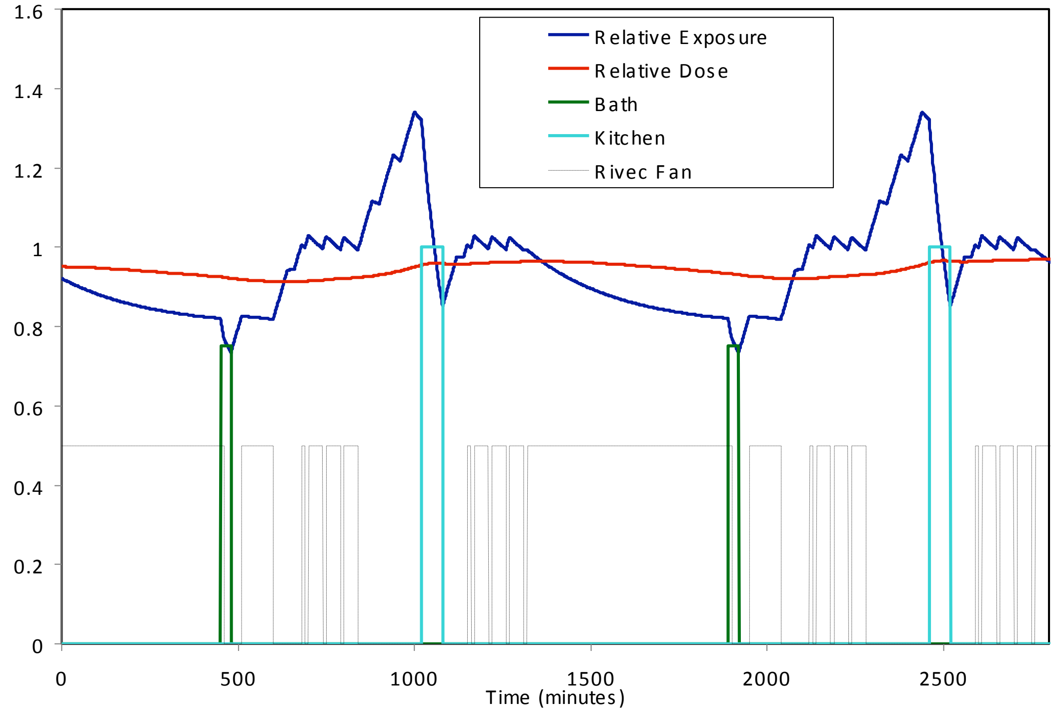

Figure 22. RIVEC operation for continuous exhaust + CFIS in CZ3 in cooling season

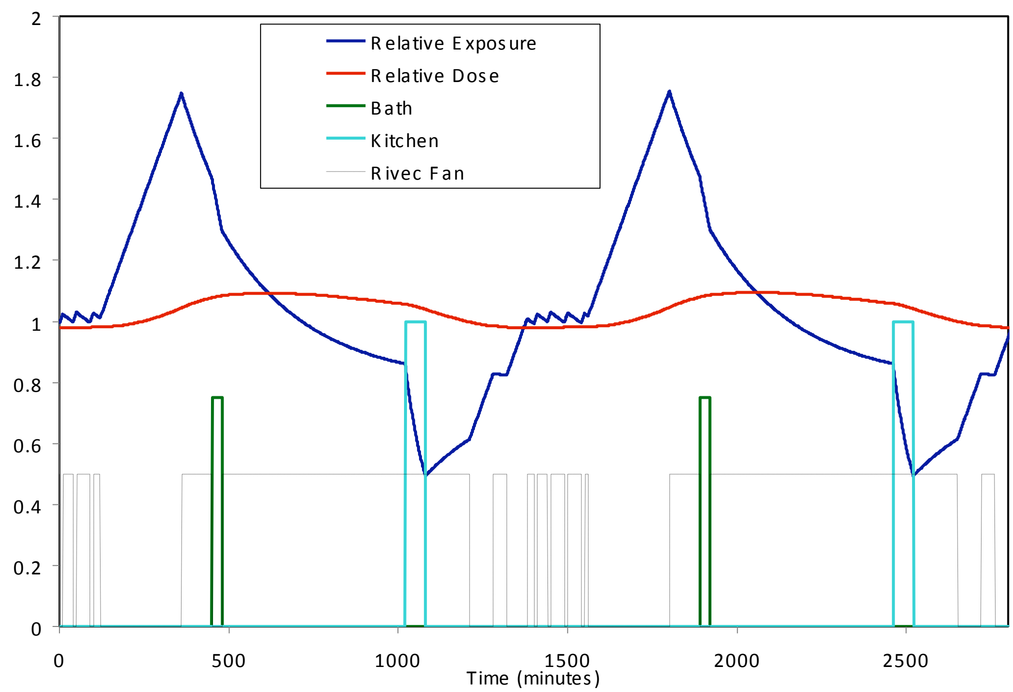

Figure 23. RIVEC operation for continuous supply in CZ3 in heating season

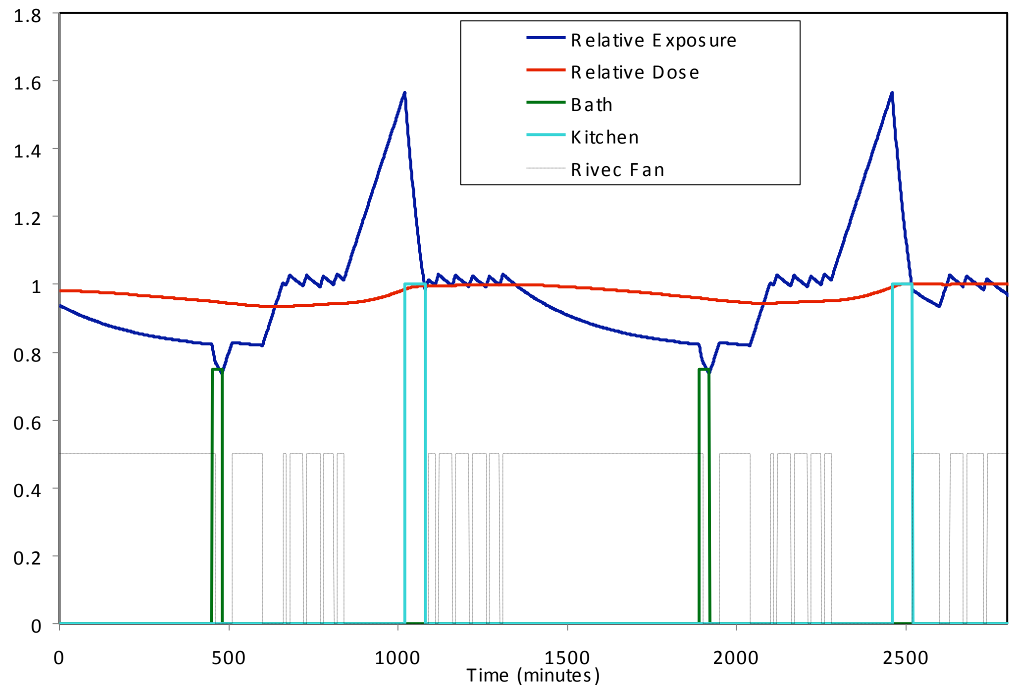

Figure 24. RIVEC operation for continuous supply in CZ3 in cooling season

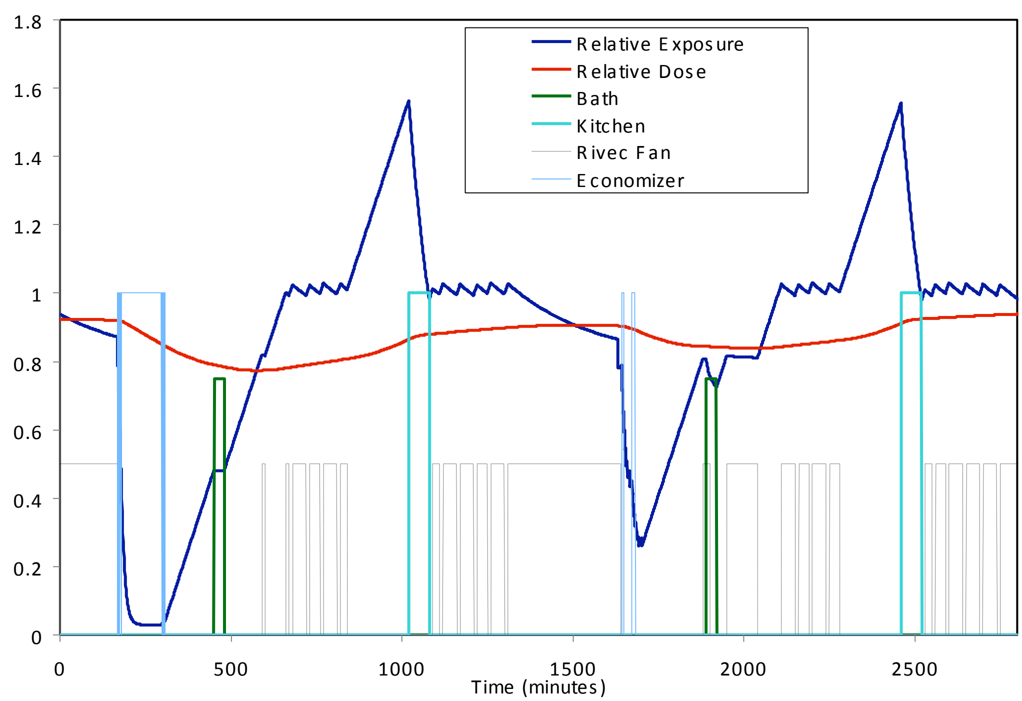

Figure 25. RIVEC operation for continuous exhaust + economizer in CZ13 in cooling season

The following figures summarize the annual energy use relative to an unvented house – so they are the extra energy – either electricity or gas- required to adequately ventilate the home. The differences between RIVEC and non-RIVEC are the savings due to the RIVEC controller. Note that the CFIS cases have a CFIS in the non-mechanically ventilated home because we are focusing on the changes made by using RIVEC to only control the designated mechanical ventilation system that is meeting ASHRAE 62.2 (in this case the continuous exhaust). Appendix A has these same figures, but with without the CFIS in the non-mechanically ventilated home to show the energy impact of using CFIS.

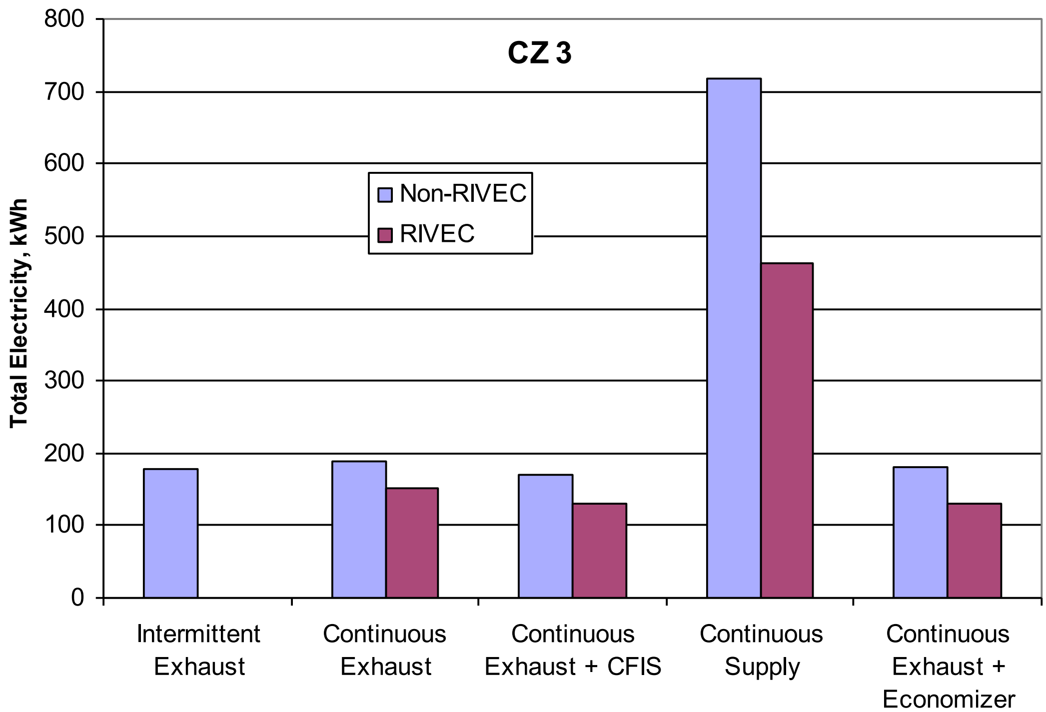

Figure 26. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

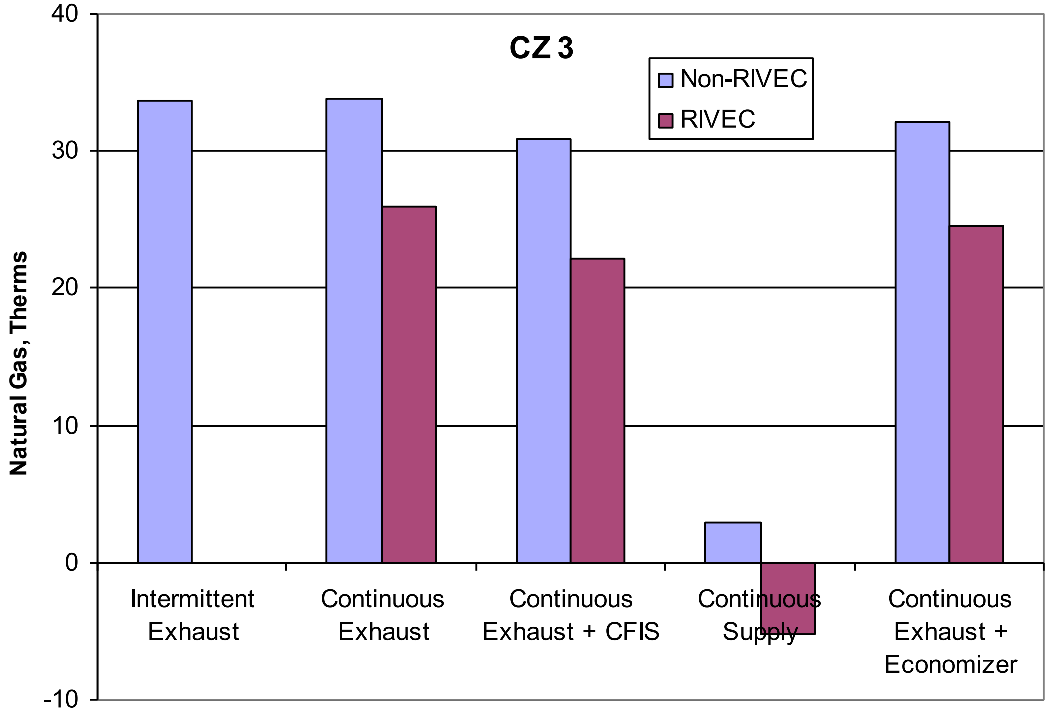

Figure 27. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

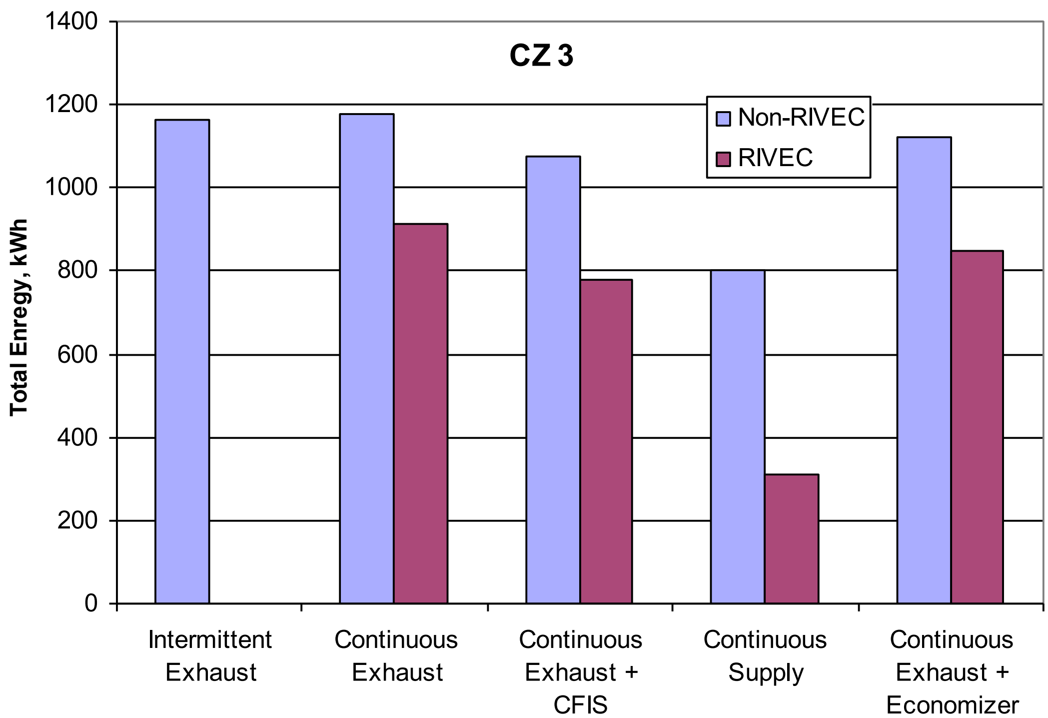

Figure 28. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

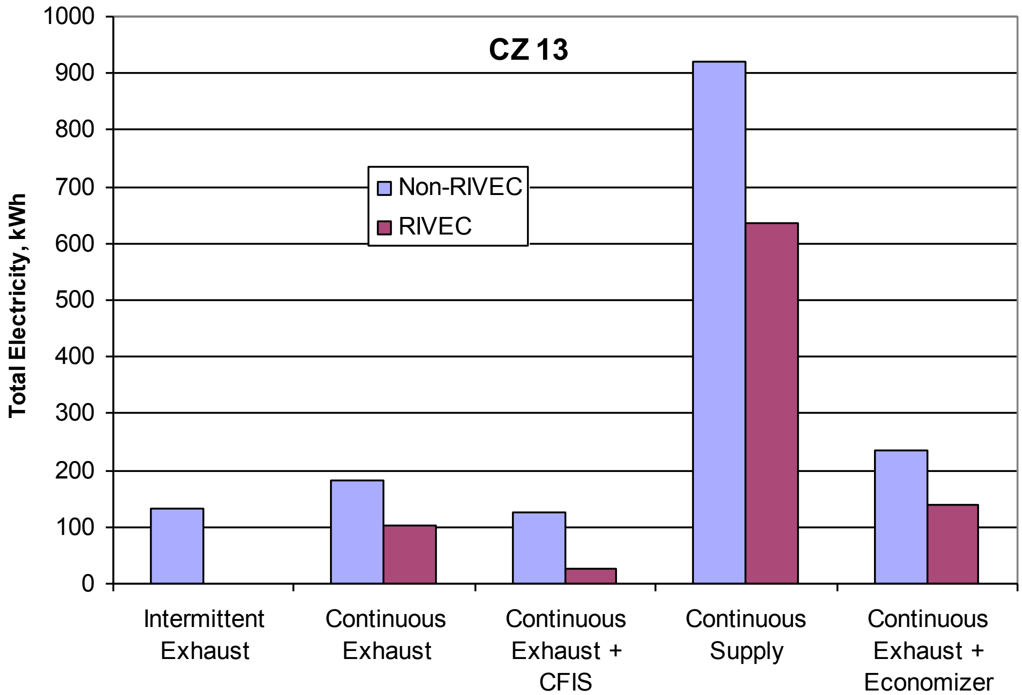

Figure 29. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

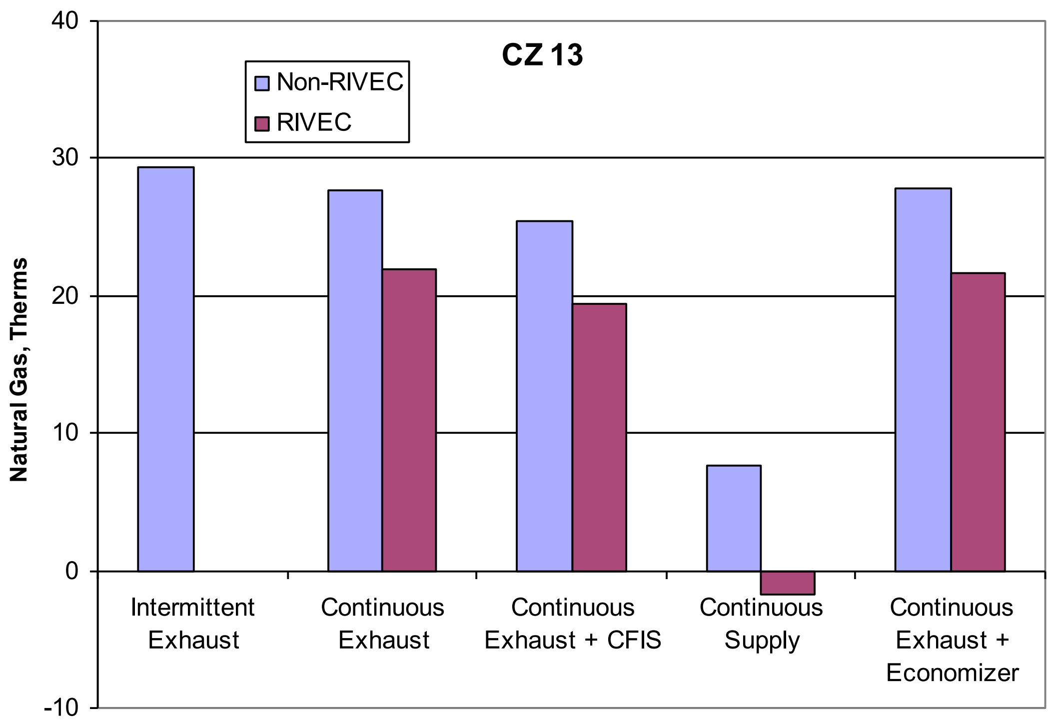

Figure 30. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

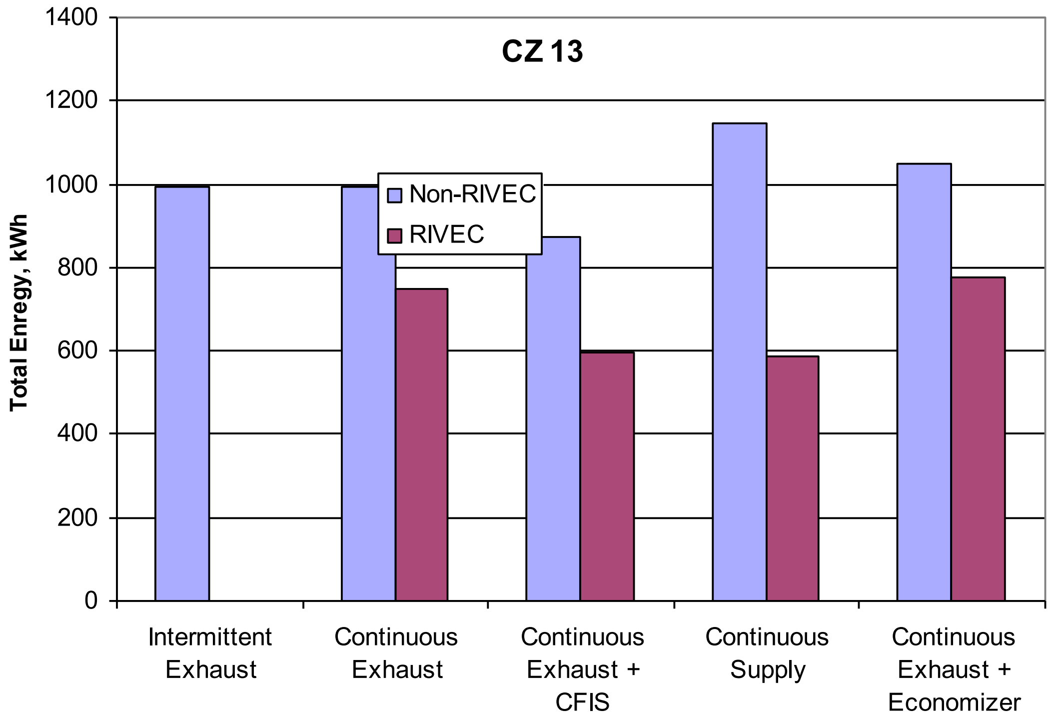

Figure 31. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

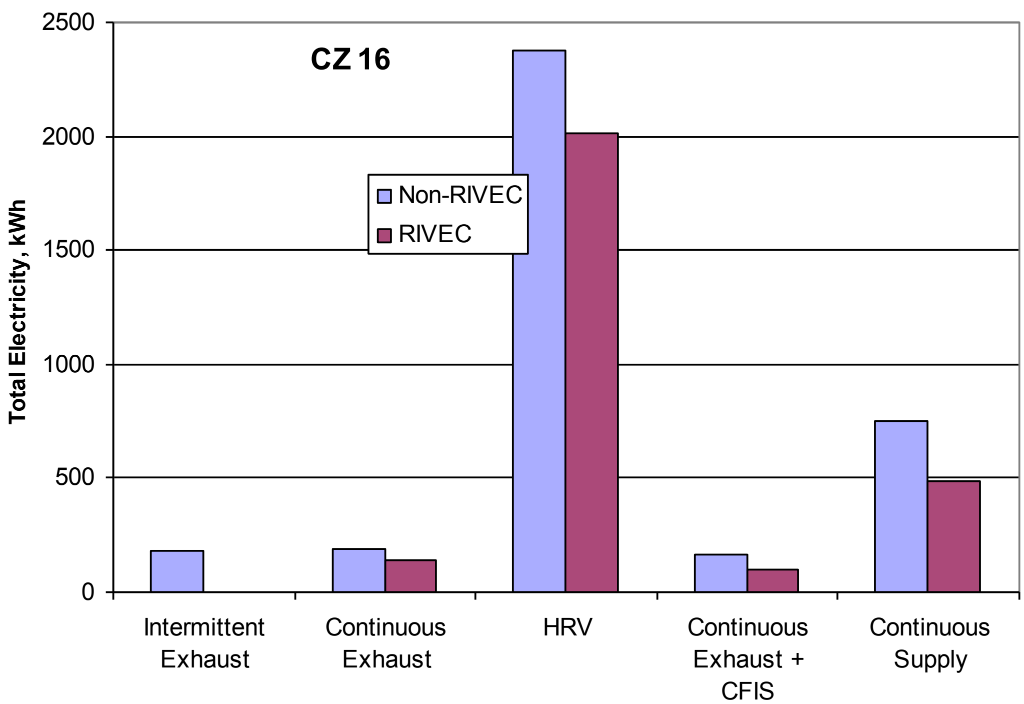

Figure 32. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16

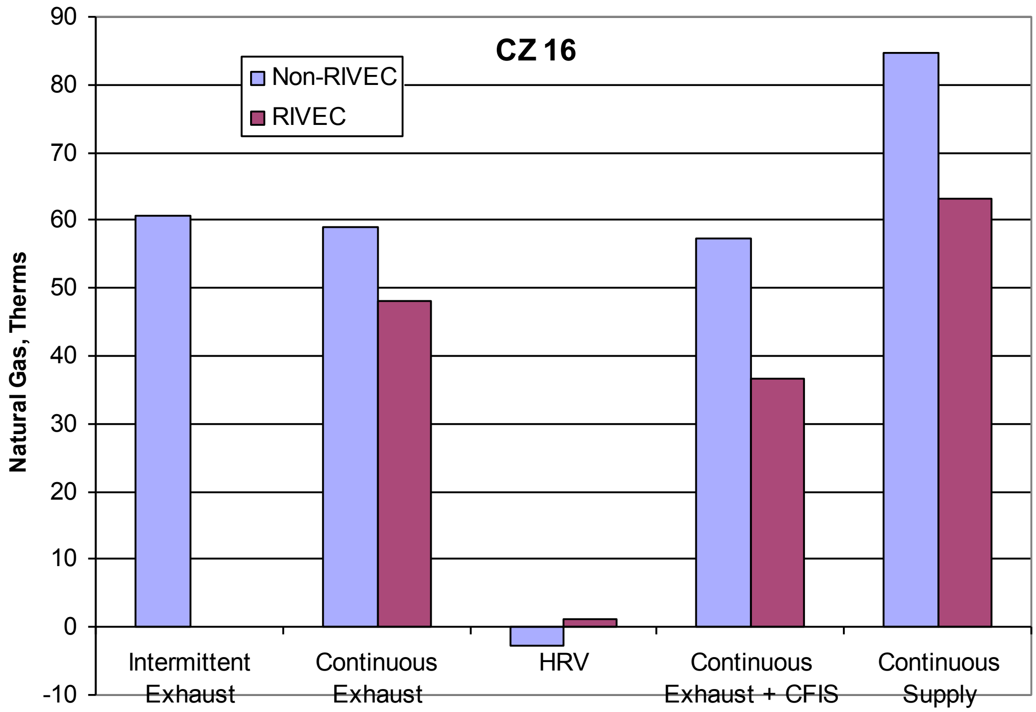

Figure 33. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16

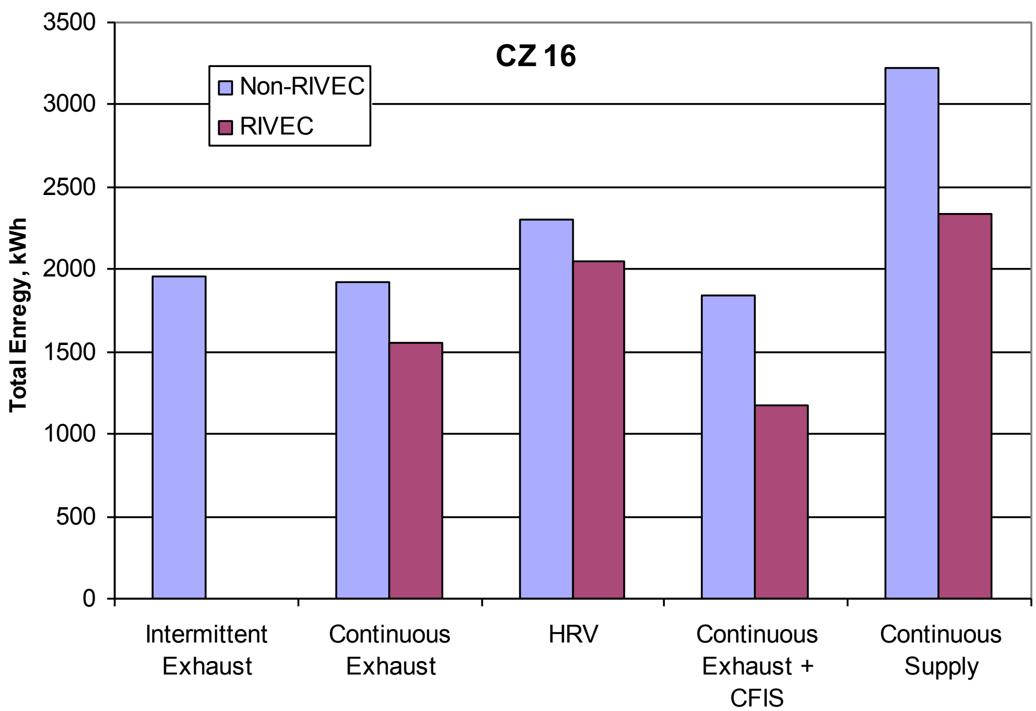

Figure 34. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16

RIVEC saves energy relative to the normal ventilation case for all the ventilation systems. The exception is that more natural gas is used for the HRV operated using RIVEC. This is because the RIVEC control leads to more operation during extreme conditions despite being off for four hours per night. It is possible that this could be changed by altering the hours that RIVEC is off for at night when heating to better match the times of greater indoor outdoor temperature difference. The following figures summarize the total energy savings from RIVEC operation.

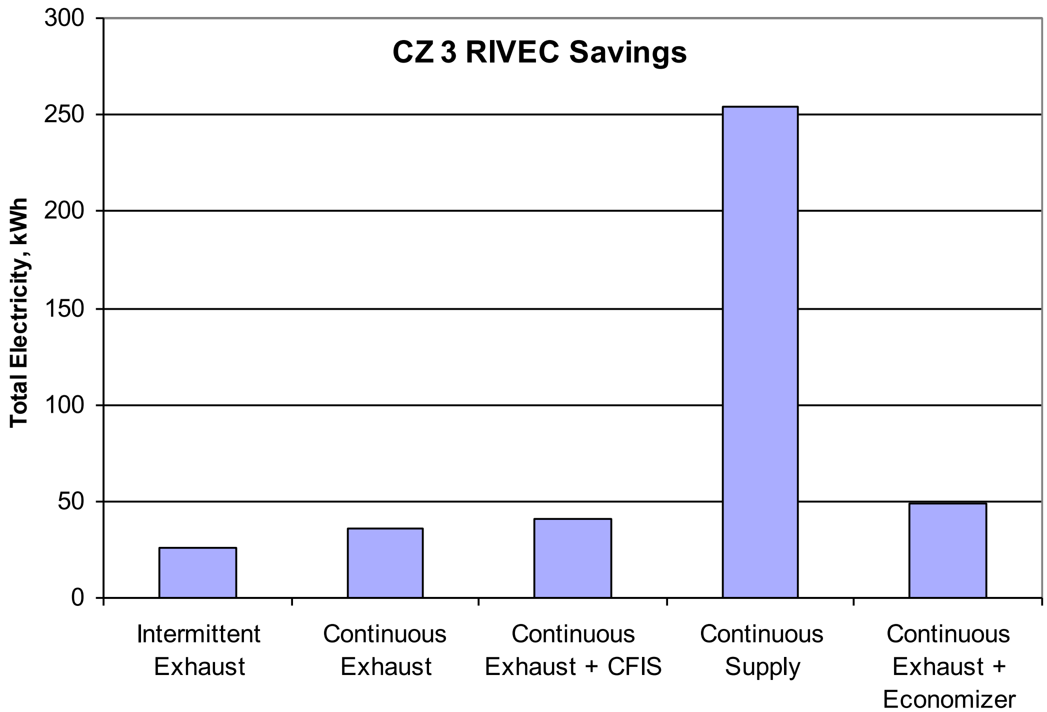

Figure 35. Total Electricity RIVEC savings in CZ3

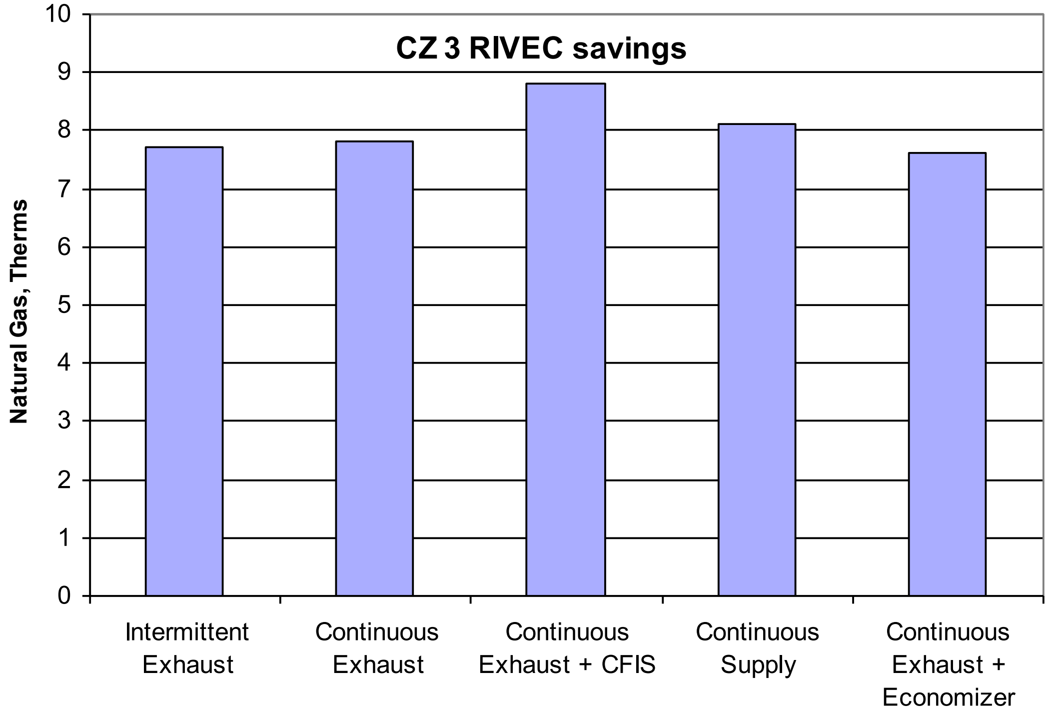

Figure 36. Natural Gas RIVEC savings in CZ3

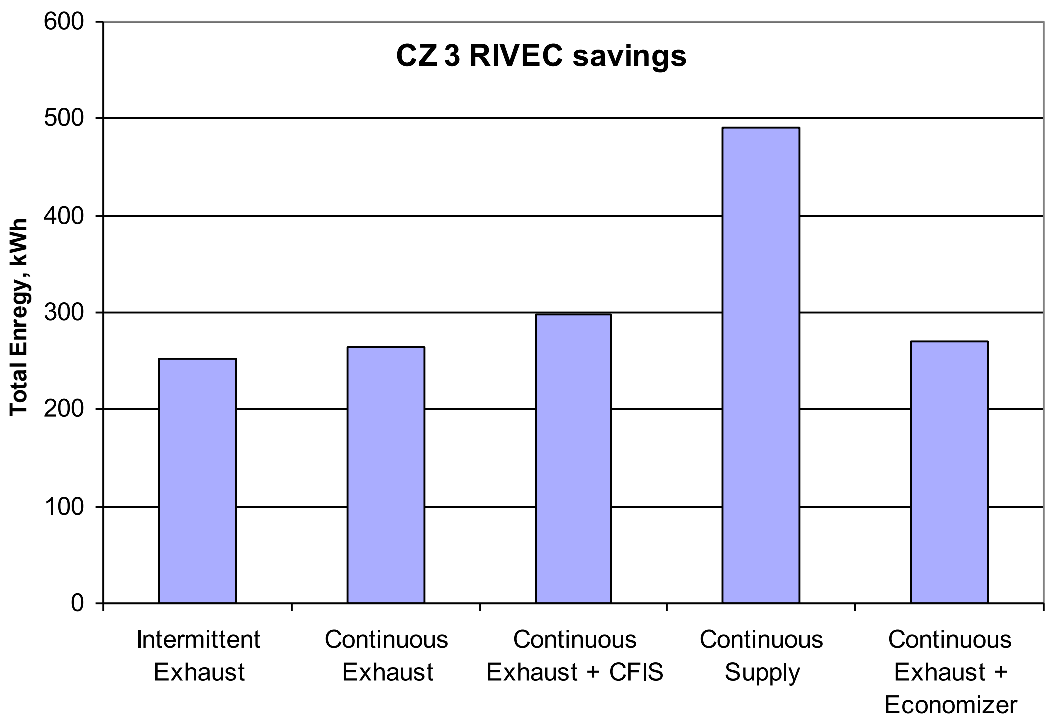

Figure 37. Total Energy RIVEC savings in CZ3

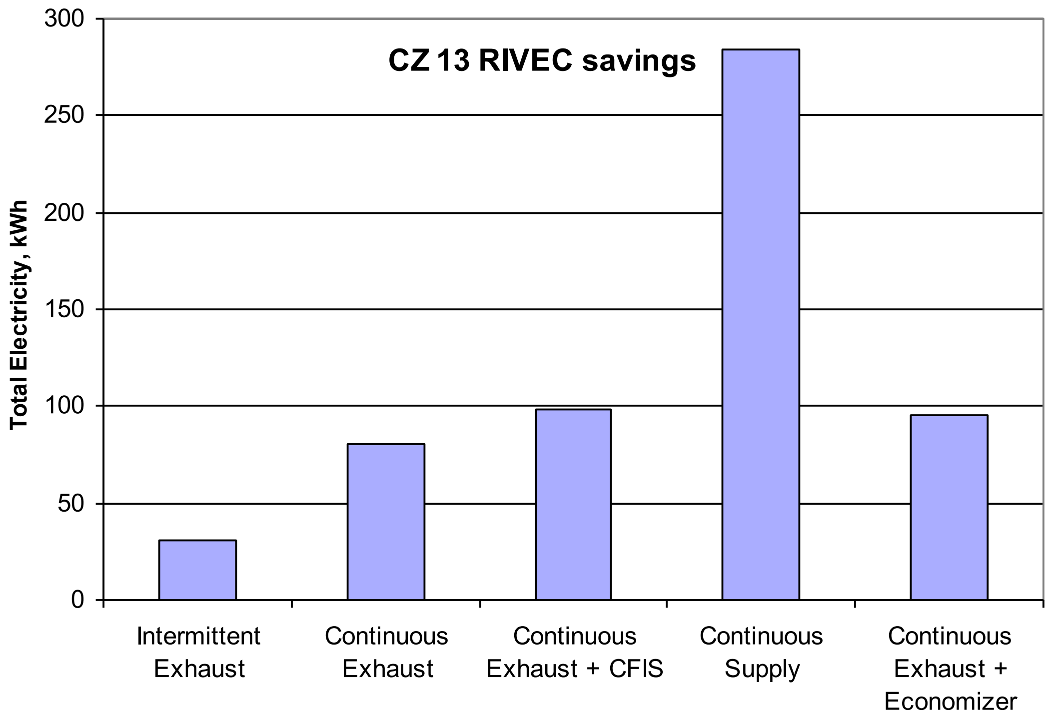

Figure 38. Total Electricity RIVEC savings in CZ13

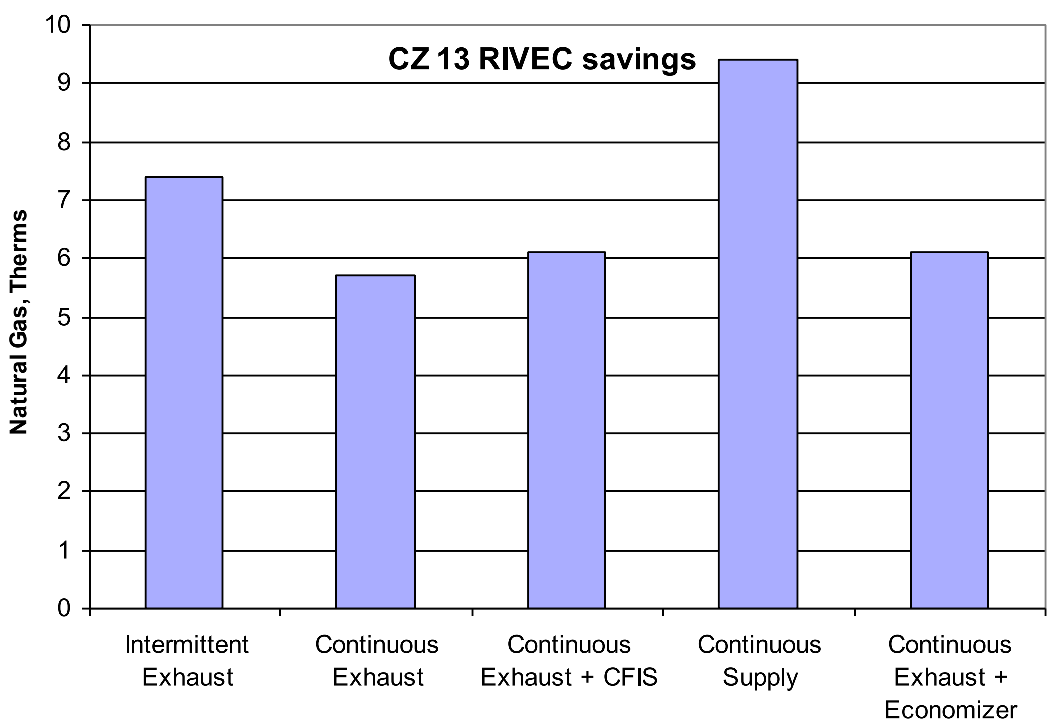

Figure 39. Natural Gas RIVEC savings in CZ13

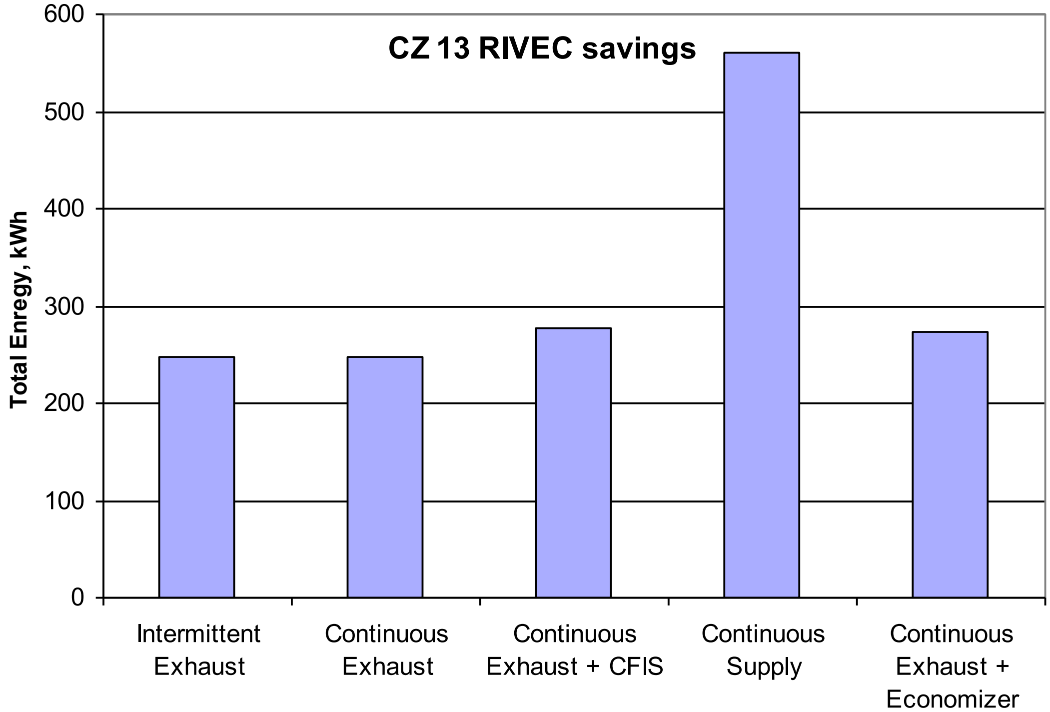

Figure 40. Total Energy RIVEC savings in CZ13

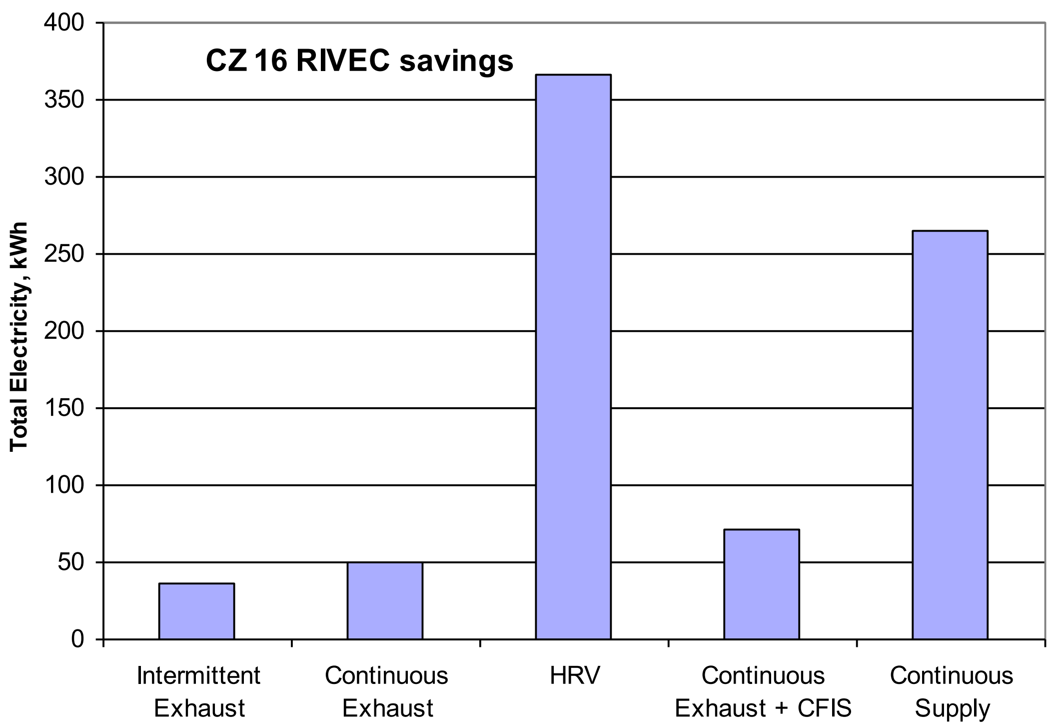

Figure 41. Total Electricity RIVEC savings in CZ16

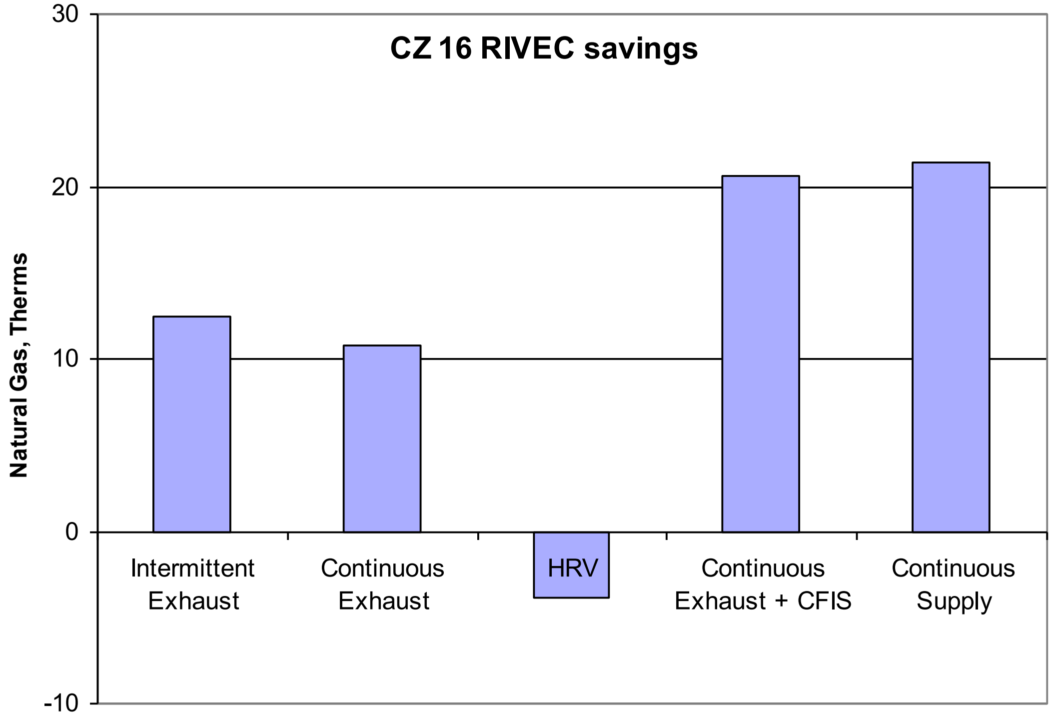

Figure 42. Natural Gas RIVEC savings in CZ16

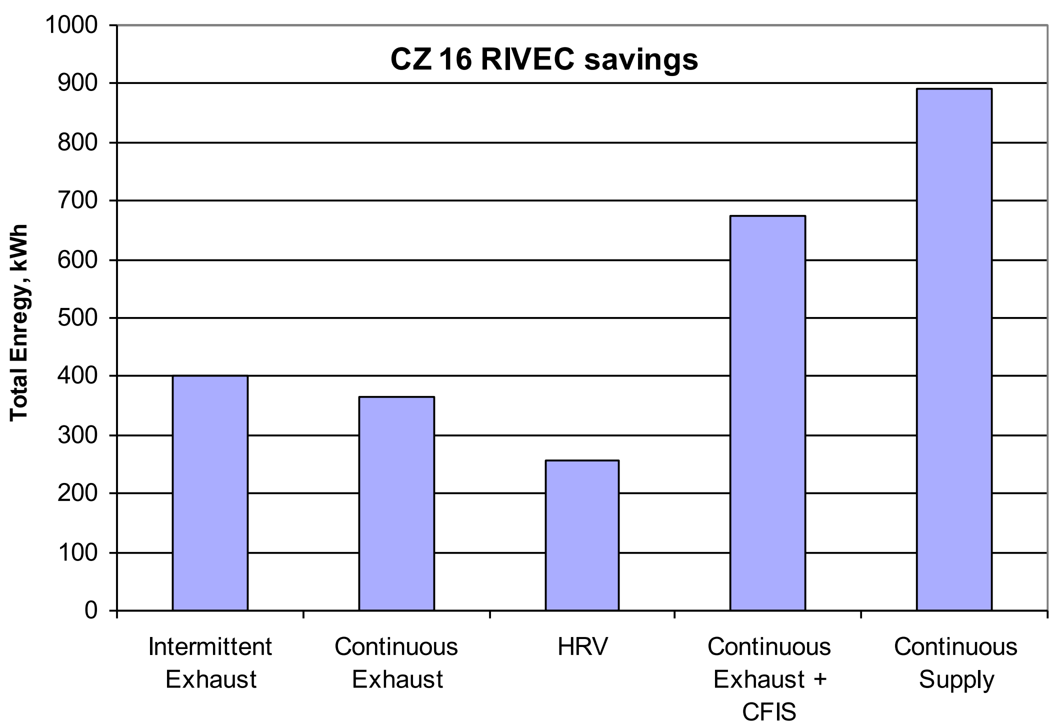

Figure 43. Total Energy RIVEC savings in CZ16

Fractional Runtime Summary

Table 13 summarizes the fractional runtime for the whole house fan. With no RIVEC controller the whole house fan would operate 525,600 minutes per year. The economizer simulation (16EISG2R) show that economizer operation leads to significant reductions in whole house fan operation using RIVEC. The other cases range from 49% to 65% fractional ontimes depending on the climate and the operation of other ventilation fans and the whole house system that is being controlled. Overall these are significant reductions in whole house system runtime.

Table 13. Fractional runtime for RIVEC controlled whole house fans

Simulation		Number of minutes on	Fractional Runtime
03EISG1R	Oakland – Continuous Exhaust	342670	0.65
03EISG3R	Oakland - Continuous Exhaust + CFIS	310250	0.59
03EISG4R	Oakland – Continuous Supply	342670	0.65
03EISG5R	Oakland – Economizer	302210	0.57
13EISG1R	Fresno – Continuous Exhaust	342670	0.65
13EISG3R	Fresno - Continuous Exhaust + CFIS	315300	0.60
13EISG4R	Fresno – Continuous Supply	342670	0.65
13EISG5R	Fresno – Economizer	256330	0.49
16EISG1R	Mt. Shasta – Continuous Exhaust	342620	0.65
16EISG2R	Mt. Shasta - HRV	157210	0.30
16EISG3R	Mt. Shasta - Continuous Exhaust + CFIS	309420	0.59
16EISG4R	Mt. Shasta – Continuous Supply	342620	0.65

Table 14 summarizes the RIVEC energy savings. The savings are relative to the same ventilation system without RIVEC control. The fractional savings are the fraction of the extra energy attributed to the whole house mechanical ventilation system – I.e., the part of the building load controlled by RIVEC. The savings are greater for some systems than others because the different ventilation systems produce different air change rates. Higher air change rate systems have more energy saving capacity with RIVEC. The energy savings for each system do not vary much from Oakland to Fresno, although the harsh climate of Mt. Shasta does show greater savings. The only anomaly is for the HRV operation where there is an increase in natural gas use because the RIVEC control leads to more operation during extreme conditions despite being off for four hours per night. It is possible that this could be changed by altering the hours that RIVEC is off at night when heating to better match the times of greater indoor outdoor temperature difference.

For California these energy savings can be translated into savings across the state if RIVEC strategies are implemented. Walker and Sherman (2006) have shown that residential ventilation systems compliant with the expected new California standards would represent between 5 and 32% of the load depending on the system chosen. RIVEC can reduce this load by at least 20%. Using this 20% gives a conservative estimate of potential savings. To estimate potential electricity savings the 84,000 GWh used for residential heating and cooling[8] is multiplied by the fraction of total building load that is infiltration load (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 7000 GWh. RIVEC saves at least 20% of this energy or 1400 GWh. For natural gas a similar calculation can be performed: 5000 million therms are used each year[9] for heating such that the 20% savings result in 83 million therms of natural gas saved per year. For an individual consumer this corresponds to reductions in annual energy bills of $20 to $60.

[8] http://www.energy.ca.gov/naturalgas/natural_gas_facts.html

[9] http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm

Table 14. Energy Saved using RIVEC						
Location	**Ventilation System**	**Air Changes per hour – Annual Average**	**Electricity (kWh)**	**Gas (Therms) [kWh]**	**Percent Savings, %**	**Annual Bill savings at $0.18/kWh and $1.75/therm**
CZ3 - Oakland	Intermittent Exhaust	0.018	26	7.7 [226]	21	18.20
CZ3 – Oakland	Continuous Exhaust	0.017	36	7.8 [229]	22	20.19
CZ3 – Oakland	Continuous Exhaust + CFIS	0.025	41	8.8 [258]	31	22.73
CZ3 – Oakland	Continuous Supply	0.021	254	8.1 [237]	18	59.94
CZ3 – Oakland	Continuous Exhaust + Economizer	0.018	48	7.6 [223]	28	22.01
CZ13 - Fresno	Intermittent Exhaust	0.021	31	7.4 [217]	23	18.47
CZ13 – Fresno	Continuous Exhaust	0.023	81	5.7 [167]	29	24.53
CZ13 – Fresno	Continuous Exhaust + CFIS	0.03	98	6.1 [179]	35	28.33
CZ13 – Fresno	Continuous Supply	0.015	284	9.4 [275]	18	67.62
CZ13 – Fresno	Continuous Exhaust + Economizer	0.034	95	6.1 [179]	44	27.84
CZ16 - Mt. Shasta	Intermittent Exhaust	0.017	36	12.5 [366]	20	28.37
CZ16 - Mt. Shasta	Continuous Exhaust	0.017	50	10.8 [316]	22	27.93
CZ16 - Mt. Shasta	HRV	0.036	367	-3.8 [-111]	13	59.36
CZ16 - Mt. Shasta	Continuous Exhaust + CFIS	0.025	71	20.6 [604]	30	48.88
CZ16 - Mt. Shasta	Continuous Supply	0.022	265	21.4 [627]	22	85.16

Critical Peak Load Reduction

RIVEC eliminates all whole-house mechanical ventilation-related loads during the daily four-hour peak load window. To determine the total peak load reduction attainable with RIVEC, the simulation data were examined to find coincident times for the RIVEC and non-RIVEC results. The coincident times were chosen based on hourly averages of the minute-by-minute data. The total power used by the blower, furnace, air conditioner and ventilation system were calculated for each hour of the year. The hourly data were sorted to find the hours of maximum heating and cooling energy consumption for the non-RIVEC case that occurred during the peak times programmed into RIVEC (i.e., 1:00 a.m. to 5:00 a.m. for heating and 3:00 p.m. to 7:00 p.m. for cooling). The energy use for corresponding hour from the RIVEC simulations was compared to the energy use for the peak hour in the non-RIVEC case. The results were averaged over the highest five energy use hours 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 conservative results in terms of energy savings, it was chosen for this analysis. The peak hour power reductions are summarized in Table 15 (the gas consumption is converted to Watts for better comparison and so that it can be combined with the blower and ventilation fan power).

Table 15. Peak Hour Power reduction due to RIVEC controlled whole house fans

Simulation	Cooling Power reduction (W)	Heating Power Reduction (W)
Oakland – Continuous Exhaust	72 (6%)	1676 (15%)
Fresno – Continuous Exhaust	45 (1%)	1553 (15%)
Mt. Shasta – Continuous Exhaust	142 (4%)	890 (5%)

The results in Table 15 show that the most significant energy savings are for heating. For cooling, the reductions are smaller due to ventilation being a smaller fraction of building load and lower indoor to outdoor temperature differences.

Conclusions

The RIVEC system has successfully achieved its stated objectives and demonstrated that there is a significant potential benefit to California in reducing energy and peak power requirement for meeting minimum ventilation standards. Specifically,

- Using smart control of residential mechanical ventilation systems can save 20-70% of its annual energy while meeting minimum ventilation requirements.

- Using smart control of residential mechanical ventilation systems can save 100% of its peak power associated with ventilation, and 1% to 6% of total power for cooling and 5% to 15% for heating while meeting minimum ventilation requirements.

- It is possible to create a ventilation controller that can implement such an approach.

Implementation of the RIVEC approach can lead to run-times of 30-70% of nominal full-time operation.

RIVEC successfully controls ventilation while still maintaining acceptable indoor air quality relative to ASHRAE 62.2.

- While preserving IAQ and eliminating peak ventilation power RIVEC can save 18-31% of ventilation energy in a mild climate (CZ3), 18-44% in a central valley climate (CZ13), or 13-30% in a cold climate (CZ16), depending on the mechanical ventilation system chosen.

Substantially higher savings may occur if occupants use equipment like dryers, exhaust fans, or economizers more than is assumed in this study.

Existing homes may be retrofit with the RIVEC technology and can show improved IAQ and/or ventilation energy savings.

RIVEC can realized as a stand-alone ventilation controller, but may be more cost-effectively commercialized if integrated with other residential controllers or home automation approaches.

Because the RIVEC can time shift ventilation within a day, it has the ability to not only reduce the total energy, but to eliminate peak ventilation-energy demand. 100% of the peak ventilation-related load can be eliminated. In addition, 1% to 6% of total (not just ventilation) peak power can be eliminated for cooling and 5% to 15% for heating. This allows consumers to reduce exposure to high peak energy prices while ensuring better grid stability for all consumers.

A related non-energy benefit is that this controller is capable of time-shifting ventilation from periods in which the outdoor air quality may be poor or dangerous.

Recommendations

Because of the success of this project it is recommended that further efforts be done to take advantage of this technology in both regulatory and voluntary programs and to advance the commercialization. Specifically,

Title 24 should be modified to provide appropriate credit for anyone using this type of technology to reduce the energy impact of required whole-house mechanical ventilation.

The benefits of using this technology in low-income weatherization and other retrofit programs targeting envelope tightening should be evaluated, including the role of infiltration.

ASHRAE Standard 62.2 should be clarified with regard to how control technology can be used to meet it, the role of minimizing outdoor air contaminants, and how to apply technologies in existing homes, especially those in which infiltration has a significant roles.

The RIVEC approach should be integrated into demand response programs.

Further analysis should be done to determine how RIVEC can be used to help protect occupants from short-term outdoor air pollution and/or toxic releases.

Home ventilating manufacturers and/or controls providers should be contacted for potential partnerships.

References

ACCA. 1986. "Manual J- Load Calculation for Residential Winter and Summer Air Conditioning - 7th Ed.". Air-Conditioning Contractors of America. Washington, DC.

ACCA. 1986. "Manual S - Residential Equipment Selection". Air-Conditioning Contractors of America. Washington, DC.

ASHRAE Standard 136-1993 (RA 2001), "A method of determining air change rates in detached dwellings," American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

ASHRAE Standard 62.2, 2004, "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings," American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, GA.

ASHRAE. 2007. "ASHRAE Standard 62.2-2007 - Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings". Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

CEC (2004) http://www.energy.ca.gov/electricity/statewide_weightavg_rates.html

California Energy Commission. 2005. “Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings.” California Energy Commission, Sacramento, CA.

Edmonds, J.A. and Ashton, W.B., 1989, “A preliminary analysis of U.S. CO_2 Emissions reduction potential from energy conservation and the substitution of natural gas for coal in the period to 2010”, Washington, D.C.: U.S. DOE, Feb. 1989 (DOE/NBB-0085).

Feustel, H.E., M.P. Modera, and A.H. Rosenfeld. 1986. "Ventilation Strategies for Different Climates," LBL-20364. Also in Proceedings of IAQ '86: Managing Indoor Air for Health and Energy Conservation, Atlanta, Georgia: ASHRAE, 1986, pp. 342-363.

McKone T.E, Sherman M.H. 2003. “Residential Ventilation Standards Scoping Study” LBNL Report #53800, 2003.

McWilliams, J. and Sherman M. 2005. “Review of Literature Related to Residential Ventilation Requirements”. LBNL 57236. Lawrence Berkeley National Laboratory, Berkeley, CA.

Price, P.N. and M.H. Sherman. 2006. "Ventilation Behavior and Household Characteristics in New California Houses," April 2006. LBNL-59620. On-line PDF version

Russell, M. Sherman M.H. ,Rudd, A. 2007. “Review of Residential Ventilation Technologies,” *HVAC&R Research J.*, **13**(II) pp. 325-348, 2007. LBNL Report 57730.

Santamouris & Wouters, Eds. 2006. *Building Ventilation: the state of the art,* Earthscan ISBN-13: 978-1-84407-130-2 2006.

Sherman, M.H. and Wilson D.J. 1986. "Relating Actual and Effective Ventilation in Determining Indoor Air Quality." Building and Environment. Vol. 21 (3/4). pp. 135-144.

Sherman, M. and D. Dickerhoff. 1994. "Air-Tightness of U.S. Dwellings" In Proceedings, 15th AIVC Conference: The Role of Ventilation, Vol. 1, Coventry, Great Britain: Air Infiltration and Ventilation Centre, pp. 225-234. LBNL-35700.

Sherman, M.H., N.E Matson. 1997. “Residential Ventilation and Energy Characteristics,” *ASHRAE Trans*. **103**(1) pp. 717-730. LBNL-39036.

Sherman, M.H. and Matson, N.E. 2002. "**Air Tightness of New U.S. Houses: A Preliminary Report** ", Lawrence Berkeley National Laboratory, LBNL-48671, 2002.

Sherman, M.H. and J.A. McWilliams. 2005. "Report on Applicability of Residential Ventilation Standards in California" June 2005, LBNL-58713.

Sherman, M.H. and Walker, I.S. 2008. “Energy Impact of Residential Ventilation Standards in California”. ASHRAE Transactions, June 2008. LBNL-61282. http://epb.lbl.gov/Publications/lbnl-61282.pdf

Sherman, M.H. 2006. “Efficacy of Intermittent Ventilation for Providing Acceptable Indoor Air Quality,” *ASHRAE Trans*. pp 93-101 Vol. 111 (I) 2006, LBL-56292

Walker, I.S. and Sherman, M.H. 2003. "Ventilation Technologies Scoping Study" LBNL-53811

Walker, I.S. and Sherman, M.H. 2006. “Evaluation of Existing Technologies for Meeting Residential Ventilation Requirements”, LBNL 59998. Lawrence Berkeley National Laboratory, Berkeley, CA.

Wilcox, B. 1990. “Air Tightness and Air Change Rates in Typical New California Homes,” Proceedings of the ACEEE 1990 Summer Study, American Council for an Energy Efficient Economy, Washington, DC.

Wilcox. 2006. Presentation for 2008 California Building Standards Workshop. http://www.energy.ca.gov/title24/2008standards/documents/2006-07-12_workshop/presentations/2006-07-17_FAN_FLOW_WATT_DRAW.PDFIn addition to the references cited above, the following literature was reviewed and is relevant to the objectives of this project.

Wray, C.P., N.E. Matson, M.H. Sherman. 2000. “Selecting Whole-House Ventilation Strategies to Meet Proposed ASHRAE Standard 62.2: Energy Cost Considerations,” *ASHRAE Transactions*, **106** (II), 2000; Report No. LBNL-44479.

Literature Related to Ventilation Requirements

American Lung Association. 2004. “American Lung Association Health House Builder Guidelines.” American Lung Association, Saint Paul, MN.

ASHRAE. 1999. “ANSI/ASHRAE Standard 52.2-1999, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size”. Atlanta, GA; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

ASHRAE. 1989. “ANSI/ASHRAE Standard 62-1989 - Ventilation for Acceptable Indoor Air Quality”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2004. “ASHRAE Standard 62.1-2004 - Ventilation and Acceptable Indoor Air Quality”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2004. “ASHRAE Standard 62.2-2004 - Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2001. “ANSI/ASHRAE Standard 90.2-2001, Energy Efficient Design of Low-Rise Residential Buildings”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1994. “ANSI/ASHRAE Standard 119-1988 (RA 94), Air Leakage Performance for Detached Single-Family Residential Buildings”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 1993. “ANSI/ASHRAE Standard 136-1993, A Method of Determining Air Change Rates in Detached Dwellings”. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Bohac, D., M. Cheple. 2002. “Ventilation and Depressurization Information for Houses Undergoing Remodeling” Minnesota Department of Commerce State Energy Office

California Energy Commission. 2005. “Title 24, Part 6, of the California Code of Regulations: California's Energy Efficiency Standards for Residential and Nonresidential Buildings.” California Energy Commission, Sacramento, CA.

CAN/CSA. 1991. “F326-M91 Residential Mechanical Ventilation Systems” Canadian Standards Association, Mississauga, Ontario.

CAN/CSA. 1990. “C260-M90 Rating the Performance of Residential Mechanical Ventilation Equipment”. Canadian Standards Association, Mississauga, Ontario.

Council of the European Community (CEC). 2003. “Directive 2002/91/EC of the European Parliament and of the Council of 16 December 2002 on the energy performance of buildings”. Official Journal of the European Communities, Brussels, January 4 2003.

Comité Européen de Normalisation (CEN). 2003. CEN prEN 14788. 2003. Ventilation for buildings: Design and dimensioning of residential ventilation systems, CEN, Brussels, 2003.

Concannon, P. 2002. “Residential Ventilation”. AIVC Technical Note 57. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

Department of Housing and Construction. 2003. “D2 Finnish Code of Building Regulations, Indoor Atmosphere and Ventilation of Buildings, Regulations and Guidelines”. Ministry of the Environment, Helsinki, Finland.

Department of the Environment and the Welsh Office. “Ventilation, The Building Regulations 2000 Approved Document F 1995.” Her Majesty’s Stationary Office. Norwich, UK.

Design Regulations BKR. 1998. “BFS 1998:38: Hygiene, health and the environment.” Swedish Board of Housing, Building and Planning, Karlskrona, Sweden

Devine, J. 1999. “Whole House Ventilation Systems Research Report”. Washington State Ventilation and Indoor Air Quality Code report.

Devine, J., Lubliner, M., and Kunkle, R. 1999. "Occupant Interaction with Washington State Ventilation and Indoor Air Quality Code mandated whole house ventilation systems: Telephone survey results." ASHRAE Transactions, Vol. 105, Part 2.

Dubrul, C. 1988. "Inhabitant Behaviour with Respect to Ventilation – a Summary Report of IEA Annex 8". AIVC Technical Note 23. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

EPA. 2005. "Energy Protection Agency Indoor Air Quality Specifications." Energy Protection Agency, Washington, DC.

Florida, State of. 2001. "Florida Building Code, Section 409, Ventilation." Florida Building Commission, Tallahassee, FL.

Fugler, D. 2004. "Analysis of Ventilation System Performance in New Ontario Houses" Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Fugler, D. 2002. "Compliance of Ventilation Systems Installed to meet Proposed Changes to the 1995 NBCC." Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Fugler, D. 2000. "Is it Worth Putting in a Better Furnace Filter?" Home Energy Volume 17, Number 3. May/June 2000. Berkeley, CA.

Grimsrud, D.T. and Hadlich; D.E. "Residential Pollutants and Ventilation Strategies: Volatile Organic Compounds and Radon", ASHRAE Transactions 105(2), pp. 849-863, 1999.

Hadlich, D.E. and Grimsrud; D.T. " Residential Pollutants and Ventilation Strategies: Moisture and

Combustion Products", ASHRAE Transactions 105(2), pp. 833-848 1999.

Hinds, William. 1999. "Aerosol Technology: properties, behavior and measurement of airborne particles" John Wiley and Sons, New York.

Hill. 1998. "Field Survey of Heat Recovery Ventilation Systems." Research Highlight Canada Mortgage and Housing Corporation, Ottawa, Ontario.

Home Ventilating Institute (HVI). 2005. "HVI Certified Products Directory". Home Ventilating Institute, Wauconda, IL

Howard-Reed, C., L. Wallace, W. Ott. 2002. "The Effect of Opening Windows on Air Change Rates in Two Homes". Journal of the Air and Waste Management Association 52:147-159.

ICC. 2003. "International Residential Code for One and Two-family Dwellings." International Code Council, Country Club Hills, IL.

ICC. 2003. “International Energy Conservation Code.” International Code Council, Country Club Hills, IL.

Janssen, John E. 1994. “The V in ASHRAE: An Historical Perspective”. ASHRAE Journal. August. Vol 36 no. 8, pg 126-132 American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Janssen, John E. 1999. “The History of Ventilation and Temperature Control”. ASHRAE Journal. October. Vol 41 no. 10, pg 48-70 American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Kaplan, J. 1986. “Development of Material Safety Data Sheets” Proceedings of the 191st American Chemical Society national meeting. New York, NY. (http://www.phys.ksu.edu/area/jrm/Safety/kaplan.html)

Kelly, K., M. Brien, and R. Stemp. 1993. “Occupant use of Ventilation Controls and Humidifiers during Cold Seasons”. Proceedings of Indoor Air ’93 Vol. 5, pp.69-72.

Klepeis, N., W.C. Nelson, W.R. Ott, J.P. Robinson, A.M. Tsang, P. Switzer, J.V. Behar, S.C. Hern, W.H. Engelmann. 2001. “The National Human Activity Pattern Survey (NHAPS) A Resource for Assessing Exposure to Environmental Pollutants”. LBNL-47713. Lawrence Berkeley National Laboratory.

Kühnl-Kinel, J. 2000. “The History of Ventilation and Air Conditioning: Is CERN up to Date With the Latest Technological Developments?” Proceedings of the Third ST Workshop, Chamonix, France. CERN Geneva, Switzerland.

Lemaire M-C, Trotignon R. 2000. “Ventilation in the French Homes: Survey of the attitudes and Behaviour of Private Citizens”. Proceedings of Innovations in Ventilation Technology, 21st Annual AIVC Conference, 2000.

Liddament, M. 1996. "A Guide to Energy Efficient Ventilation”. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

Liddament, M. 2001. “Occupant Impact”. AIVC Technical Note 53. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

Maldonado, E.A.B., J.E. Woods. 1983. “Ventilation Efficiency as a Means if Characterizing Air Distribution in a Building for Indoor Air Quality Evaluation.” ASHRAE Transactions. Vol 89, Part 2B, pp.496-506. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

McKone, T.E., and Sherman, M.H., 2003. “Residential Ventilation Standards Scoping Study.” LBNL-53800. Lawrence Berkeley National Laboratory, Berkeley, CA.

Ministère de l’équipment, des transports et du logement. 1982. “Arrêté du 24.03.82 relatif à l’aération des logements.” Journaux Officiels du 27 mars 1982, Paris, France.

Minnesota, State of. 2000. “Minnesota Rules Chapter 7672: Energy Code”. Department of Public Service, Minneapolis, MN.

Modera, M.P., 1989. "Residential Duct System leakage: Magnitude, Impacts and Potential for Reduction," ASHRAE Transactions 95 (2): 561-569. LBL-26575.

Nagda, N.L., R. W. Krug and M.D. Koontz. 1995. “Depressurization, Backdrafting and Spillage from Vented Gas Appliances – A Literature Review”. Report of ENERGEN Consulting, Inc. and GEOMET Technologies, Inc. to Gas Research Institute and Pacific Gas and Electric Company, GRI-95/0426. November.

NFPA. 1999a. “NFPA 54-1999 National Fuel Gas Code”. Quincy, MA: National Fire Protection Association.

NFPA. 1999b. “National Fuel Gas Code Handbook” 4th Edition. Editor: T.C. Lemoff. Quincy, MA: National Fire Protection Association.

NRC. 1995. “National Building Code of Canada 1995.” National Research Council Canada, Ottawa, ON.

Oseland, N. 1995. “Occupant Response to Passive Stack Ventilation: A UK Postal Survey.” 16th AIVC Conference Proceedings, Vol 2. Air Infiltration and Ventilation Centre, Sint-Stevens-Woluwe, Belgium.

Phillips, T., E. Mulberg, P Jenkins. 1990. “Activity Patterns of California Adults and Adolescents: Appliance use, Ventilation Practices, and Building Occupancy”. Proceedings, 1990 ACEEE Summer Study on Energy Efficient Buildings, Vol. 4. pp.187-196. Washington, D.C.: American Council for an Energy-Efficient Economy.

Quirt, J.D. 1991. “Field measurement of sound from residential ventilation fans”. CMHC (client report prepared by the Institute for Research in Construction, National Research Council of Canada), Ottawa.

Roberson, J. 2004. “Effect of Building Airtightness and Fan Size on the Performance of Mechanical Ventilation Systems in New U.S. Homes: A Critique of ASHRAE Standard 62.2-2003”. Master of Science Thesis, University of California, Berkeley.

Seppanen, O., W.J. Fisk and M.J. Mendell. 1999. Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings, Indoor Air 9(4):226-252.

Seppanen, O., W.J. Fisk and M.J. Mendell. 2002. Ventilation rates and health. ASHRAE Journal 44(8):56-58.

Sheltersource, Inc. 2002. “Evaluating Minnesota Homes Final Report.” Prepared for the Minnesota Department of Commerce.

Sherman, M.H., Chan W. R., 2004. "Building Airtightness: Research and Practice" LBNL-53356. Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherman, M.. 2004. "ASHRAE's First Residential Ventilation Standard"   Submitted to Buildings IX Conf, Clearwater FL, LBNL-54331.

Sherman, M.H. and Matson, N.E. 2002. "Air Tightness of New U.S. Houses: A Preliminary Report " LBNL-48671 Lawrence Berkeley National Laboratory, Berkeley, CA.

Sherman, M., and Matson, N., "Residential Ventilation and Energy Characteristics", LBL-39036 Lawrence Berkeley National Laboratory, Berkeley, CA.
Sherman, M. and Dickerhoff, D. 1994. “Air-tightness of U. S. Dwellings.”, LBL-35700 Lawrence Berkeley National Laboratory, Berkeley, CA.

Thatcher, T., A. Lei, R. Moreno-Jackson, R. Sextro, W. Nazaroff. 2002. “Effects of room furnishings and air speed on particle deposition rates indoors”. Atmospheric Environment 36 (2002) 1811-1819.

Tsang, Andy and Neil Klepeis. 1996. "Descriptive Statistics Tables from a Detailed Analysis of the National Human Activity Pattern Survey (NHAPS) Data." Report for the National Exposure Research Laboratory, Las Vegas, NV, July 1996.

Wargocki P., J. Sundell, W. Bischof G. Brundrett, P.O. Fanger, F. Gyntelberg, S.O. Hanssen, P. Harrison, A.Pickering O. Seppanen P. Wouters. 2002. Ventilation and health in non-industrial indoor environments: report from a European Multidisciplinary Scientific Consensus Meeting (EUROVEN). Indoor Air 12(2):113-128.

Washington State Building Code Council. 2000. “Washington State Ventilation and Indoor Air Quality Code.” Washington State Building Code Council, Olympia, WA

Wiley, J., J.P. Robinson, T. Piazza, K. Garrett, K. Cirksena, Y. Cheng, G. Martin. 1991. “Activity Patterns of California Residents”. Final Report to the Air Resources Board. Contract Number A6-177-33.

Wilson, D.J. and I.S. Walker. 1992. “Feasibility of Passive Ventilation by Constant Area Vents to Maintain Indoor Air Quality in Houses.” Proceedings of Indoor Air Quality ’92 Conference. Joint Conference: ASHRAE/ACGIH/AIHA. San Francisco, CA.

Wray, Craig. 2001. “Guidelines for Residential Commissioning” LBNL-48767. Lawrence Berkeley National Laboratory, Berkeley, CA.

Literature Related to Ventilation Technologies

Abushakra, B., Walker, I., and Sherman, M. 2003. “A Study of Pressure Losses in Residential Air Distribution Systems.” LBNL Report-49700. Lawrence Berkeley Laboratory. Berkeley, CA.

Allard, F. and Ghiaus, C. 2005. “Natural Ventilation in Urban Environment.” AIVC – State of the Art in Ventilation.

Ask, A. 2003. "Ventilation and Air Leakage," ASHRAE Journal. American Society of Heating Refrigerating and Air-Conditioning Engineers. November, 2003. pp.28-34.

Axley, J. W. 2001. "Residential Passive Ventilation Systems: Evaluation and Design." AIVC Technical Note 58, Air Infiltration and Ventilation Center.

Bansal, N.K., Mathur, R., and Bhandari, M.S. 1994. "A Study of Solar Chimney Assisted Wind Towed System for Natural Ventilation in Buildings." Building and Environment. Vol. 29. pp. 495-500.

Barley, C. D. 2002. "Barriers to Improved Ventilation in Production Housing." Proceedings of Indoor Air 2002 (9th International Conference on Indoor Air Quality and Climate). Monterey, Ca. Vol. 2. pp. 896-901.

Bonnefous, Y.C., A.J. Gadgil, and W.J. Fisk. 1994. Energy and Buildings vol. 21 (1). pp.15-22. LBL-33795. and 1992."Impact of Subslab Ventilation Technique on Residential Ventilation Rate and Energy Costs." In Proceedings, 13th AIVC Conference: Ventilation for Energy Efficiency and Optimum Indoor Air Quality, Coventry, Great Britain: Air Infiltration and Ventilation Centre. pp. 431-439.

Building Science Corporation. Westford, MA. http://www.buildingscience.com/resources/mechanical/default.htm

CMHC. 2003. "Penetration of Outdoor Particles into a Residence." Research Highlights. June 2003. Canadian Mortgage and Housing Corporation. http://www.cmhc.ca/

Delmotte, C. 2003. "Airtightness of Ventilation Ducts." Ventilation Information Paper No. 1, AIVC. Air Infiltration and Ventilation Center.

Dorer, V. Breer, D. 1998. "Residential Mechanical Ventilation Systems: Performance Criteria and Evaluations." Energy and Buildings. Vol. 27. pp. 247-255.

Dorer, V., Pfeiffer, A. and Weber, A. 2004. "Parameters for the Design of Demand Controlled Hybrid Ventilation Systems for Residential Buildings." Air Infiltration and Ventilation Centre. (RESHYVENT).

Dorer, V., Tanner, C. and Weber, A. 2004. "Airtightness of Buildings." Ventilation Information Paper No. 8, AIVC. Air Infiltration and Ventilation Center.

Emmerich, S.J, Dols, W.S., "LoopDA: A Natural Ventilation System Design and Analysis Tool," pp. 291-298 Proc 8th Int. IPBSA Conf. (2003)

Emmerich S.J. Nabinger, S. J. "Measurement and Simulation of The IAQ Impact of Particle Air Cleaners in a Single-Zone Building," pp. 223-244 Vol 7 (3), *HVAC&R Research J*. ASHRAE, Atlanta, GA, 2001.

Fugler, D., Bowser, D. 2002. "Reducing Particulate Levels in Houses." Indoor Air 2002: Proceedings of the 9th International Conference on Indoor Air Quality and Climate. Monterey, California.

Geros V, Santamouris M, Papanikolaou N and Guarraccino G. 2001. “Night Ventilation in Urban Environments.” Proc. AIVC Conference. Bath, UK, 2001.

Grimsrud, D.T. and Hadlich, D.E. 1999. “Residential Pollutants and Ventilation Strategies: Volatile Organic Compounds and Radon.” ASHRAE Transactions,.Vol. 105, Pt. 2.

Hadlich, D.E. and D.T. Grimsrud. 1999. “Residential Pollutants and Ventilation Strategies: Moisture and Combustion Products.” ASHRAE Transactions. Vol. 105, Pt. 2.

Hayashi, M. and Yamada, H. 1996. “Performance of a passive Ventilation System Using Beam space as a Fresh Air Chamber. Indoor Air 1996: 7th International cnoference on Indoor air Quality and Climate, Nagoya, Japan.

Heiselberg, P. 2005. “Hybrid Ventilation.” in "Ventilation: A State of the Art Review" [James & James]. Air Infiltration and Ventilation Center 2005.

Hekmat, D., H.E. Feustel, and M.P. Modera. 1986."Ventilation Strategies and their Impacts on the Energy Consumption and Indoor Air Quality in Single-Family Residences," Energy and Buildings. Vol. 9. pp. 239-251. LBL-19376.

Holton, J.K., M.J. Kokayko, and T.R. Beggs. 1997. “Comparative Evaluation of Ventilation Systems.” ASHRAE Transactions. Vol. 103, Pt. 1.

HVI 2005. “Certified Home Ventilating Products Directory”. Home Ventilating Institute. Arlington Heights, Illinois. (http://www.hvi.org/directory/).

Jaros, M., Charvat, K. 2004. “Solar Chimneys for Residential Ventilation.” AIVC 25th Conference. pp. 19-24.

Khedari, J., Rachapradit, N., and Hirunlabh, J. 2003. “Field Study of Performance of Solar Chimney with Air-conditioned Building.” Energy. Vol. 28. Pp. 1099-1114.

Levin, H. 2004. “Indoor Air Pollutants Part 2: Description of Pollutants and Control/Mitigation Measures.” AIVC Ventilation and Information Paper No. 7. Air Infiltration and Ventilation Centre.

Li, Y. and Heiselberg P. 2003. “Analysis Methods for Natural and Hybrid Ventilation – A Critical Literature Review and Recent Developments.” International Journal of Ventilation. Vol.1. pp. 3-20.

Modera, M. 1993. “Characterizing the Performance of Residential Air Distribution Systems.” Energy and Buildings. Vol. 20. pp. 65-75.

Oikos Green Building Source. 1995. “Controlled Ventilation Options for Builders.” Energy Source Builder Newsletter. No. 39. http://oikos.com/esb/index.html - 39 .

Oldham, D. J., de Salis, M. H., and Sharples, D. J. 2004. “Reducing the Ingress of Urban Noise through Natural Ventilation Openings.” Indoor Air. Vol. 14. Suppl 8. pp. 118-126.

Orme, M. 1998. “Energy Impact of Ventilation: Estimates for the Service and Residential Sectors.” AIVC Technical Note 49. Air Infiltration and Ventilation Center.

Orme, M. 2001. “Estimates of the Energy Impact of Ventilation and Associated Financial Expenditures.” Energy and Buildings. Vol. 33. pp.199-205.

Partti-Pellinen, K. Marttila, O. et.al. 2000. “Penetration of Nitrogen Oxides and Particles from Outdoor into Indoor Air and Removal of the Pollutants through Filtration of Incoming Air.” Indoor Air. Vol. 10. pp. 126-132.

Reardon, J. and Shaw, C. 1997. “Evaluation of Five Simple Ventilation Strategies Suitable for Houses Without forced-Air Heating.” ASHRAE Transactions. Vol. 103(1). pp. 731-744.

Roberson, J.A., Brown, R.E., Koomey J.G., et.al. 1998. “Ventilation Strategies for Energy-Efficient Production Homes.” LBNL-Report- 40378 Lawrence Berkeley National Laboratory, Berkeley, CA.

Rudd, A. 2005. Table 1. Cost estimates for mechanical ventilation systems.

Rudd, A. 1999. “Air Distribution Fan and Outside Air Damper Recycling Control.” Heating Air Conditioning and Refrigeration News. 5 July 1999. pp. 45.

Rudd, A., Lstiburek, J. and Ueno, K. 2003. “Residential Dehumidification and Ventilation Systems Research for Hot, Humid Climates.” AIVC 24th Conference and BETEC Conference – Ventilation, Humidity Control, and Energy. pp.355-360.

Rudd, A, Lstiburek J, 2001. “Clean Breathing in Production Homes.” Home Energy Magazine, May/June, Energy Auditor & Retrofiter, Inc., Berkeley, CA.

Rudd, A. and Lstiburek, J. 2000. “Measurement of Ventilation and Interzonal Distribution in Single Family Houses.” Proceedings of ASHRAE Annual Meeting. June 24-28, 2000. Minneapolis, MN.

Rudd, A. and Lstiburek, J. 1998. “Design/Sizing Methodology and Economic Evaluation of Central-Fan-Integrated Supply Ventilation Systems.” Proceedings of the 1998 ACEEE Summer Study on Energy Efficiency in Buildings. 23-28 August 1998. Pacific Grove, California. American Council for an Energy Efficient Economy. Washington, D.C.

Seppanen, O. 2004. “Effect of Ventilation on Health and other Human Responses.” published in "Ventilation: A State of the Art Review", [ames & James, 2005.

Seppanen, O. and Fisk, W. 2004. “Summary of Human Responses to Ventilation.” Indoor Air. Vol. 14(7), pp. 102-118.

Shao, L., Riffiat, S. B., and Gan, G. 1998 “Heat Recovery with Low Pressure Loss for Natural Ventilation.” Energy in Buildings. Vol. 28, pp. 179-184.

Sheltersource Inc. 2002. “Evaluating Minnesota Homes – A Final Report.” Minnesota Department of Commerce.

Sherman, M.H. 1990. "Air Infiltration Measurement Techniques." In Proceedings, 10th AIVC Conference: Progress and Trends in Air Infiltration and Ventilation Research. Vol. 1. Conventry, Great Britain: Air Infiltration and Ventilation Centre. pp. 63-87. LBL-27656.

Sherman, M.H 1992. "Superposition in Infiltration Modelling." Indoor Air. Vol. 2. Pp. 101-114.

Sherman M.H., "Simplified Modeling for Infiltration and Radon Entry", Proc. ASHRAE/ DOE/BTECC Conference, *Thermal Performance of the Exterior Envelopes of Buildings Conference V* (addendum), Clearwater Beach, FL, American Society of Heating, Refrigerating and Air-conditioning Engineers, 1992a. [LBL-31305]

Sherman, M.H. 1995. "The Use of Blower-Door Data." Indoor Air. Vol. 5. pp.215-224.

Sherman, M.H. 2004."ASHRAE & Residential Ventilation." ASHRAE Journal. Vol.46(1). pp. S149-156. Lawrence Berkeley Laboratory Report LBNL-53776.

Sherman, M. H. and Hodgson A.T.. 2004."Formaldehyde as a Basis for Residential Ventilation Rates." Indoor Air. Vol. 14 (1). pp. 2-8. (LBNL-49577).

Sherman, M.H. and N. Matson. 1993."Ventilation-Energy Liabilities in U.S. Dwellings." In Proceedings 14th AIVC Conference: Energy Impact of Ventilation and Air Infiltration, Coventry, Great Britain:Air Infiltration and Ventilation Centre. pp. 23-39. LBL-33890.

Sherman, M.H and Matson, N.E., 2002. "Air Leakage in New U.S. Housing." LBNL Report LBNL-48671. Lawrence Berkeley National Laboratory, Berkeley, California.

Sherman, M.H. and Matson, N.E, 2003. "Reducing Indoor Residential Exposures to Outdoor Pollutants." Technical Note AIVC 58. Air Infiltration and Ventilation Centre.

Sherman, M.H. and McWilliams, J.A. 2005. "Report on Applicability of Residential Ventilation Standards in California." LBNL-56292. Lawrence Berkeley National Laboratory, Berkeley, California.

Thatcher, T. and Layton, D. 1995. "Deposition, Resuspension, and Penetration of Particles within a Residence." Atmospheric and Environment. Vol. 29. Pp. 1487-1497.

Thatcher, T., McKone, T., *et.al*. 2001. "Factors Effecting the Concentrations of Outdoor Particles Indoors (COPI): Identification of Data Needs and Existing Data." Lawrence Berkeley National Laboratory Report - 49321.

Veld, P. O. and Passlack-Zwaans, C. 1998. "IEA ANNEX 27: Evaluation and Demonstration of Domestic Ventilation Systems. Assessments on Noise." Energy and Buildings. Vol. 27. pp. 263-273.

Walker, I. 2003. "Register Closing Effects on Forced Air Heating System Performance." LBNL Report-54005. Lawrence Berkeley National Laboratory, Berkeley, CA.

Walker, I.S., and Sherman, M.H. 2003. "Ventilation Technologies Scoping Study." LBNL-53811. Lawrence Berkeley National Laboratory, Berkeley, CA.

Walker, I.S. and Sherman, M.H. 2003. "Heat Recovery in Building Envelopes." Proc. AIVC BETEC 2003 Conference. Washington DC. LBNL 53484.

Wallace, L. A., Emmerich, S. J., and Howard-Reed, C. 2004. "Effect of Central Fans and In-duct Filters on Deposition Rates of Ultrafine Particles in an Occupied Townhouse." Atmospheric Environment. Vol. 38. pp. 405-413.

Wilson, D.J., and Walker, I.S. 1992. "Feasibility of Passive Ventilation by Constant Area Vents to Maintain Indoor Air Quality in Houses." Proc. Indoor Air Quality. ASHRAE/ACGIH/AIHA Conference. San Francisco, California. October 1992. ASHRAE, Atlanta, GA.

Wray, C., Matson, N., Sherman, M. 2000. "Selecting Whole-House Ventilation Strategies to meet proposed ASHARAE standard 62.2: Energy Cost considerations." LBNL-44479. Lawrence Berkeley National Laboratory, Berkeley, CA.

Yang, L. *et. al.* 2005. "Investigating potential of Natural Driving Forces for Ventilation in Four Major Cities in China." Building and Environment. Vol. 40. pp. 738-746.

Yoshino, H., Liu, J., et. al. 2003. "Performance analysis on hybrid ventilation system for residential buildings using a test house." Indoor Air. Vol. 13. p. 28.

Partial List of Residential Ventilation Manufacturers' Websites

The listing below is not intended to be exhaustive and no recommendation is express or implied by it.

Home Ventilating Institute (http://www.hvi.org)

Founded in 1955, HVI today represents a wide range of home ventilating products manufactured by companies in the United States, Canada, Asia, and Europe, producing the majority of the residential ventilation products sold in North America. Sound and performance ratings for a wide variety of products are listed by HVI.. The full list of manufacturers with HVI-certified products can be found at http://www.hvi.org/manudist/memberswithHVICP.html Specific manufacturers of interest follow:

American Aldes (http://www.americanaldes.com/)

American ALDES offers a full range of engineered ventilation products to help maintain healthy indoor air quality. High quality fans are designed for continuous operation. They deliver reliable air flow under real world conditions. With unique technology, such as the Constant Airflow Regulator, ALDES can assure designers and contractors simple installation, while occupants enjoy truly effective ventilation. In addition to a full range of residential ventilation products, the new "VentZone" system allows for demand controlled residential ventilation.

Aprilaire

(http://www.aprilaire.com/index.php?znfAction=ProductsCat&category=ventilation)

Aprilaire has a whole range of IAQ-related products and specifically two ventilation systems: 1) a Central-Fan Integrated Supply system and a heat recovery ventilator.

Broan-Nutone

(http://www.broan.com)

The Broan-NuTone Group is headquartered in Hartford, Wis. and employs more than 3,200 people in six countries on three continents. It is North America's largest producer of residential ventilation products such as range hoods, ventilation fans and indoor air quality products.

FanTech

(http://www.fantech.net)

For more than 2 decades, Fantech has been researching, designing and bringing to market "Ventilation Solutions" that ensure better indoor air quality in the buildings where we work and live. Core products include iunline fans for bathroom exhaust, dryer boosting and radon mitigation and a full line of indoor air quality equipment such as Heat Recovery and Energy Recovery ventilators and Whole House HEPA Filtration. Fantech's strength and stability comes from its alliance with its parent company. Systemair, Sweden. Systemair's global network of 50 subsidiaries on three continents makes the Systemair Group one of the larges air movement companies in the world.

Honeywell

(http://yourhome.honeywell.com/Consumer/Cultures/en-US/Products/Ventilation/)

Honeywell makes a line of economy ventilation that is based on a central fan integrated supply system and a line of energy efficient ventilation using heat or energy recovery ventilators.

Panasonic
(http://www2.panasonic.com/consumer-electronics/learn/Building-Products/Ventilation-Systems/)

Panasonic makes a line of very quiet and energy efficient fans including ceiling insert fans, wall fans, inline fans and energy recovery ventilators as part of their Building Products section.

Therma-Stor
(http://www.thermastor.com/Residential-Ventilation-Products/)

Therma-Stor LLC, located in Madison, Wisconsin, was established in 1977 to apply advanced heat transfer technologies to residential and commercial markets. Beginning with heat recovery water heaters, Therma-Stor now also manufactures a line of residential dehumidifiers, which includes the Santa Fe series of free-standing dehumidifiers and the Ultra-Aire series of whole house ventilating dehumidifiers. Therma-Stor also offers HI-E Dry commercial dehumidifiers and the Phoenix line of restoration equipment for dehumidification, air scrubbing, water extraction, and evaporative drying.

Venmar
(http://www.venmar.com)

For more than 25 years, Venmar Ventilation has been one of North America's leading manufacturers of innovative Indoor Air Quality products for commercial and residential applications. Today, with over one million homeowners among its customers, Venmar, a Canadian company, continues to manufacture a full range of products. From kitchen range hoods and attic ventilators to filtration and ventilation systems, all of our products are recognized as the industry standard for quality, styling, reliability, and an optimally healthy indoor air environment.

Appendix A. RIVEC energy savings without CFIS in the non-mechanically ventilated home.

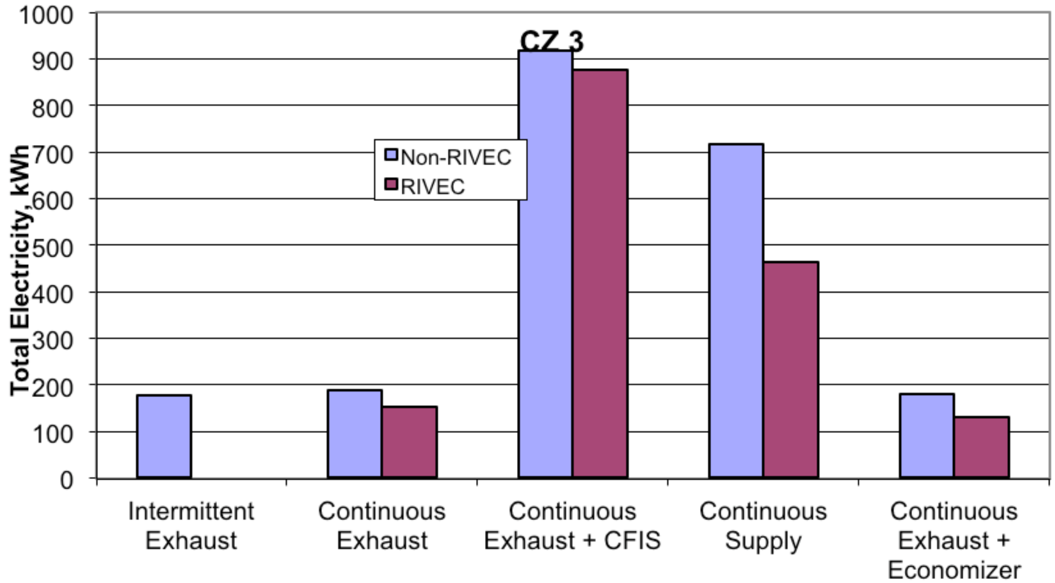

Figure A1. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

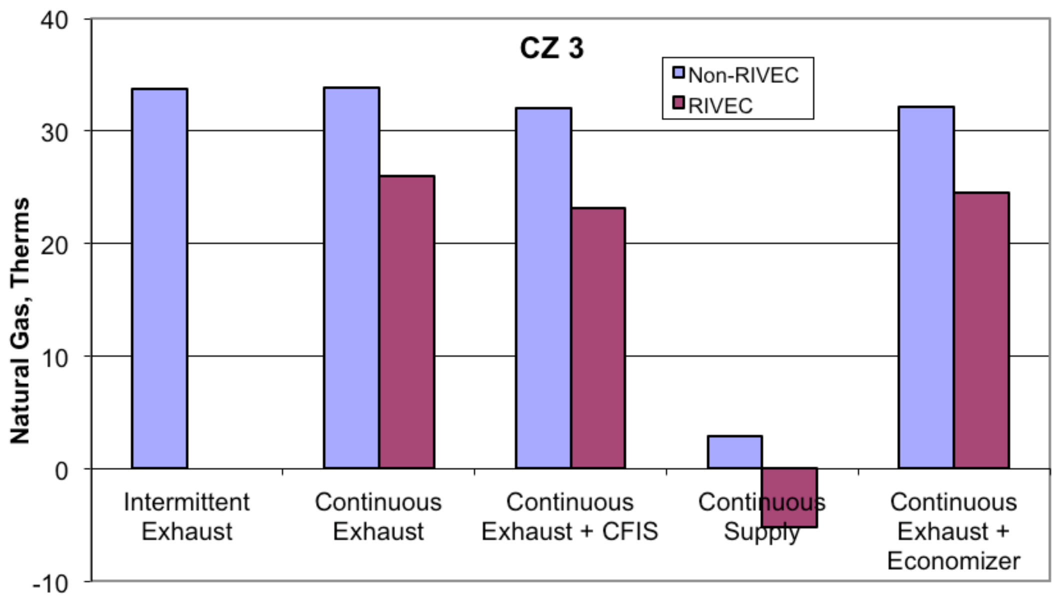

Figure A2. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

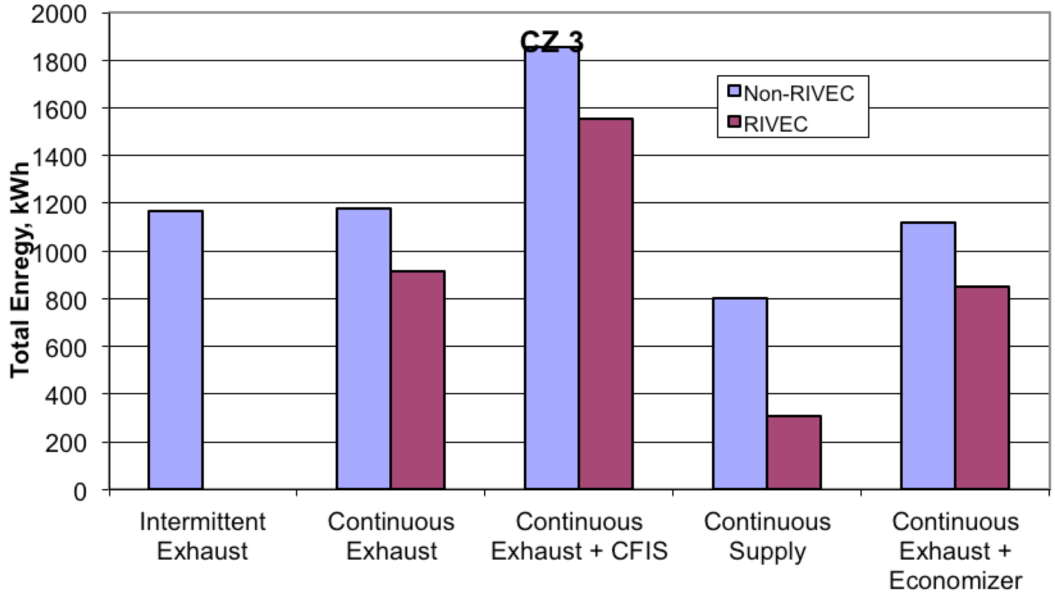

Figure A3. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ3

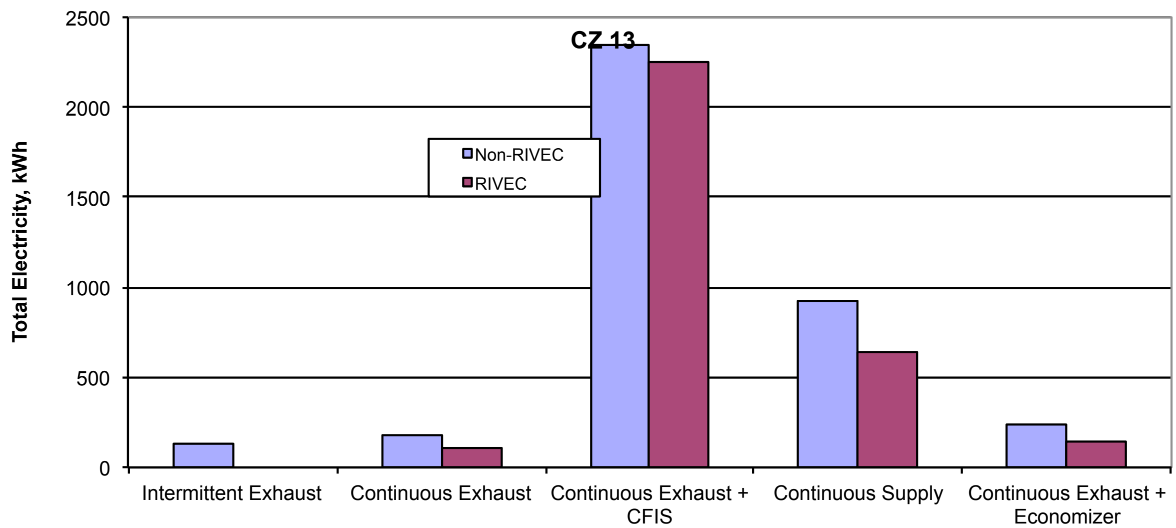

Figure A4. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

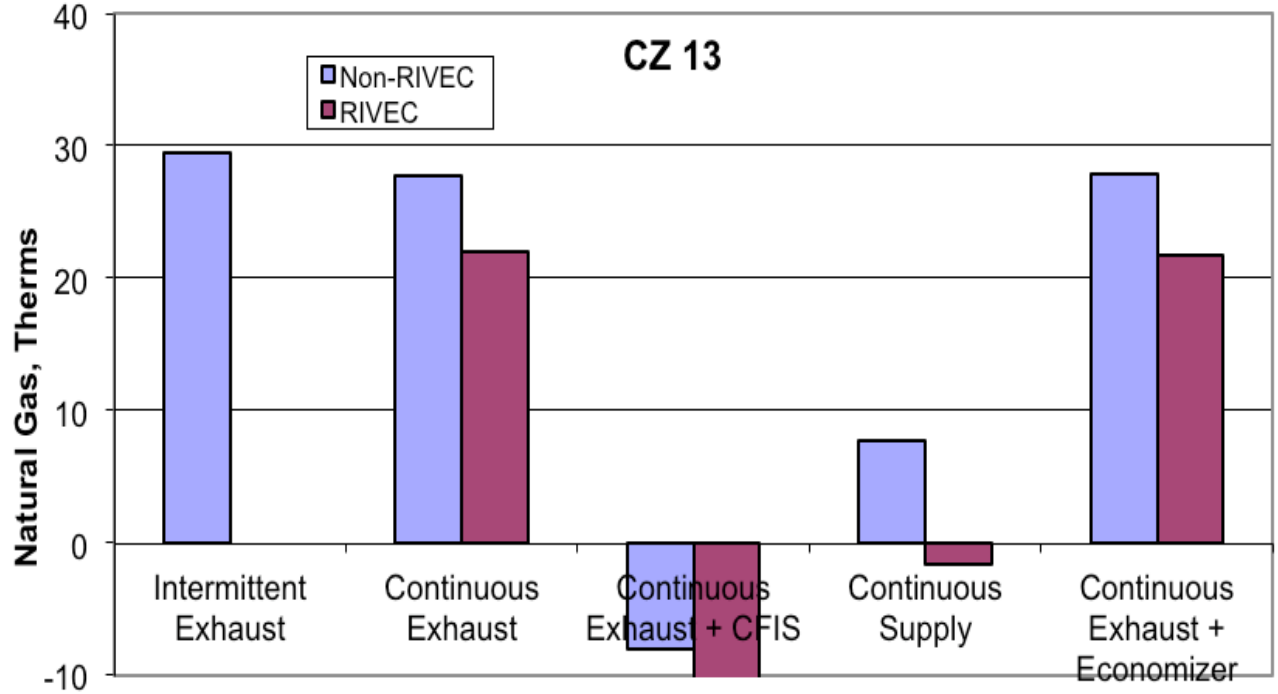

Figure A5. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

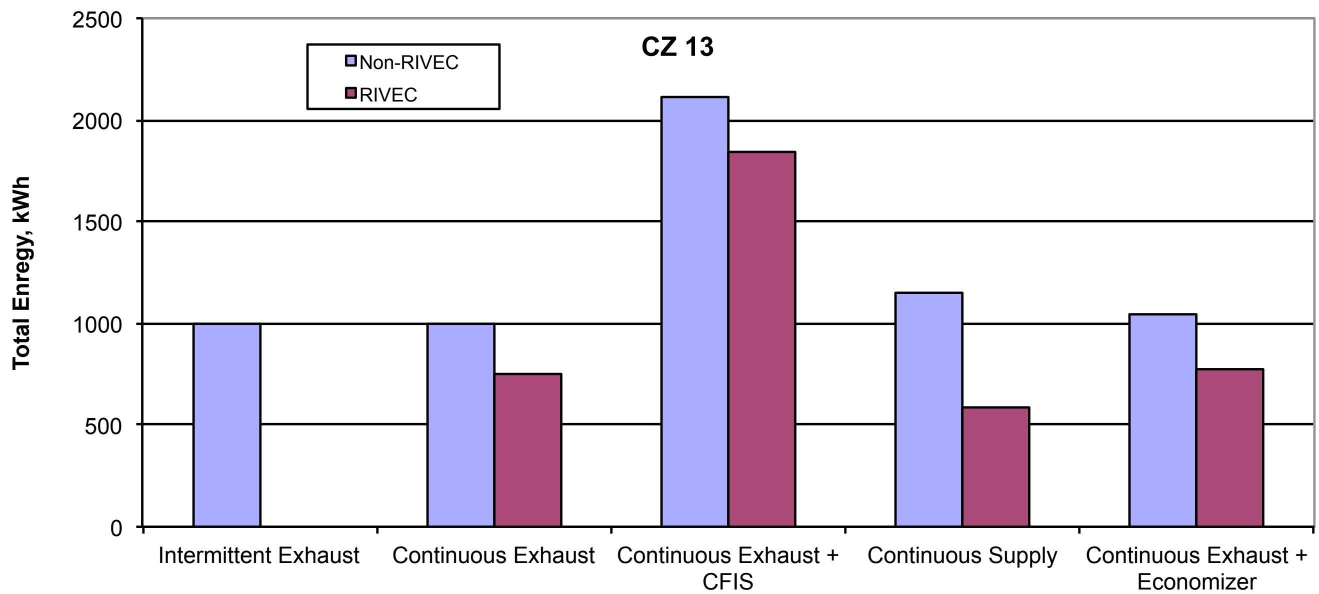

Figure A6. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ13

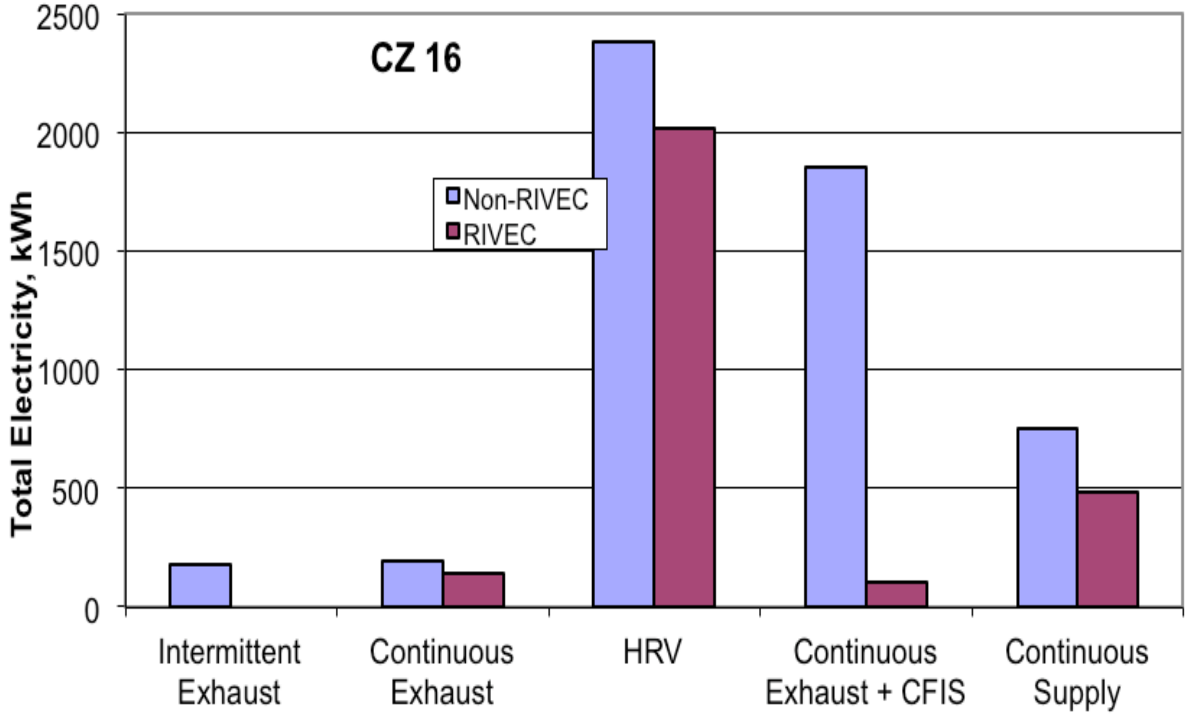

Figure A7. Additional Electricity use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16

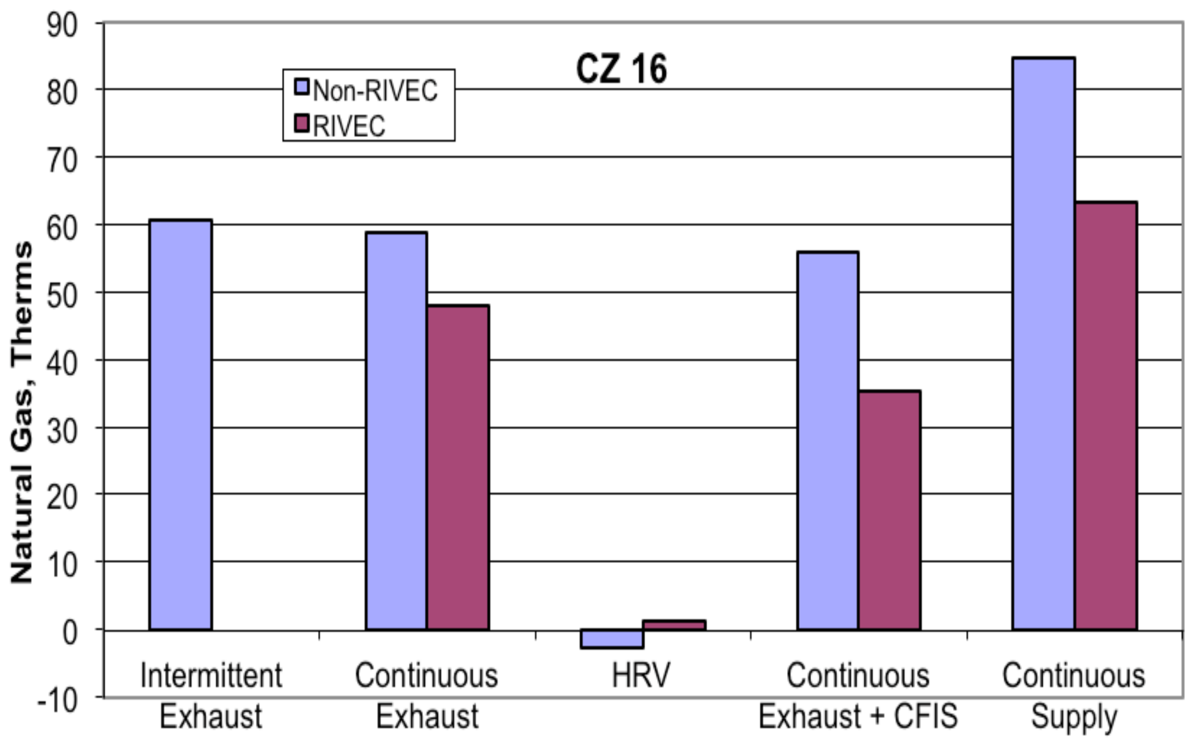

Figure A8. Additional Natural Gas use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16

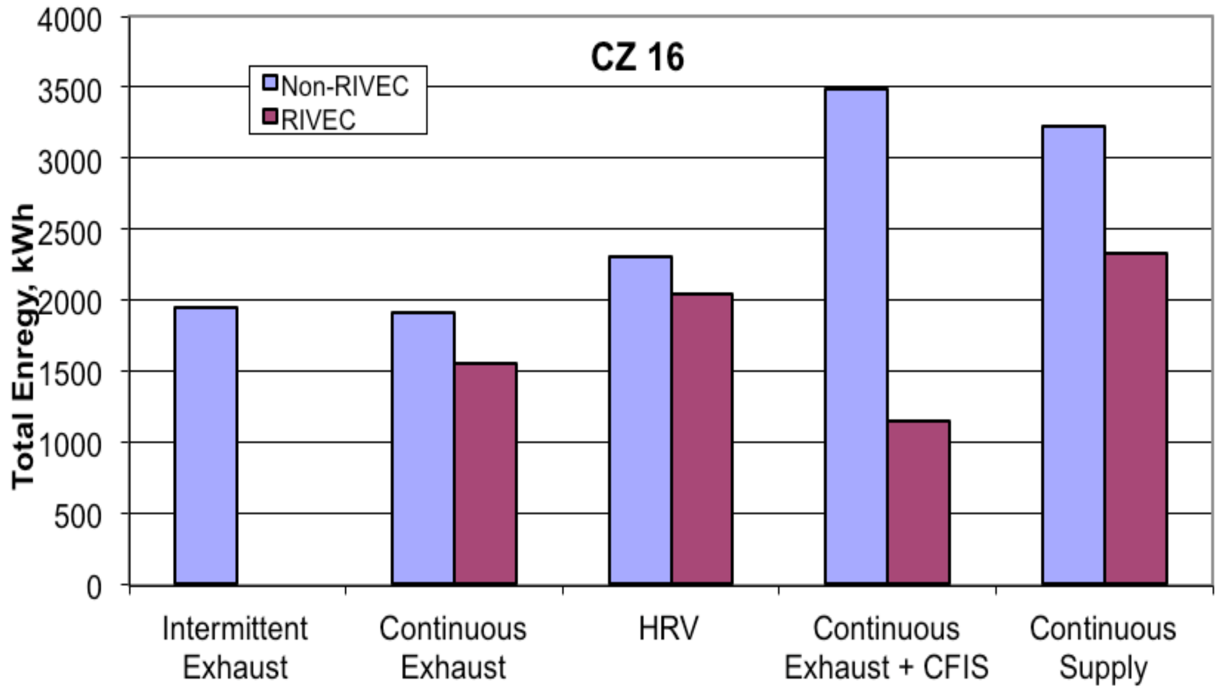

Figure A9. Additional Total Energy use for non-RIVEC and RIVEC operation relative to a non-mechanically ventilated home in CZ16