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Commissioning Residential Ventilation Systems: A Combined Assessment of Energy and Air Quality Potential Values

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Disclaimer

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Abstract

Due to changes in building codes, whole-house mechanical ventilation systems are being installed in new California homes. Few measurements are available, but the limited data suggest that these systems don't always perform as code and forecasts predict. Such deficiencies occur because systems are usually field assembled without design specifications, and there is no consistent process to identify and correct problems. The value of such activities in terms of reducing energy use and improving indoor air quality (IAQ) is poorly understood. Commissioning such systems when they are installed or during subsequent building retrofits is a step towards eliminating deficiencies and optimizing the tradeoff between energy use and IAQ.

The goal of this study was to determine the potential value of commissioning residential whole-house ventilation systems that are intended to comply with California's Title 24 residential ventilation requirements. A computer modeling approach was used to assess the impact on occupant health and building energy use of malfunctioning whole-house ventilation systems. Energy and IAQ impacts were quantified and then compared by using the Time Dependent Valuation (TDV) approach for energy and a Disability Adjusted Life Year (DALY) approach for IAQ. Results showed that health benefits dominated energy benefits independently of house size and climate. Providing minimum airflow rates to comply with ASHRAE Standard 62.2 alone was not a sufficient metric for commissioning whole-house ventilation systems, due to the strong dependence of IAQ on indoor contaminant emission rates. Instead, the metric should be net present value of the combined energy and IAQ benefits to the consumer and commissioning cost decisions should be made relative to that value even if that means ventilating to exceed the ASHRAE 62.2 minimum.

As a consequence of combining IAQ and energy costs, the beginnings of an approach to optimize the ventilation rates of homes was established.

KEYWORDS

Residential, Commissioning, Ventilation, Energy, Indoor Air Quality, Health, Valuation

1. INTRODUCTION

Until recently, whole-house mechanical ventilation systems were seldom installed in California houses. In 2008 to address potential concerns about diminished indoor air quality (IAQ), the state's Title 24 Energy Code (CEC, 2008b) mandated that new homes comply with ASHRAE Standard 62.2 (ASHRAE, 2010) that provides requirements for residential ventilation. These include minimum airflows for whole-house mechanical ventilation and for local exhausts, and maximum total net exhaust airflows for combustion safety. Standard 62.2 also states that delivered mechanical ventilation airflows must be measured, except for local exhaust systems with ducts that meet prescriptive sizing requirements or manufacturer's design criteria.

Few measurements are available, but the limited data indicate that, where installed, these systems may not always perform as expected. For example, Offerman (2009a) found that, of the few ducted outdoor air systems in use, many did not run often enough with sufficient flow to provide adequate ventilation. Such deficiencies occur because systems are field assembled (usually without design specifications), there is no consistent process to identify and correct problems, and the value of such activities in terms of reducing energy use and improving IAQ is unknown. Commissioning such systems when they are installed or during subsequent building retrofits is a step towards eliminating deficiencies and optimizing the tradeoff between energy use and acceptable IAQ.

According to ASHRAE, the building commissioning process is defined as "a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria" (ASHRAE, 2005). This means that commissioning is the process of determining if a system is working as intended. The results of the commissioning process are used to determine whether changes to the building system are warranted. Every commissioning process includes three principal elements: metrics, diagnostics, and norms (Wray et al., 2003a, 2003b, 2003c). For whole buildings, there are two broad

performance metrics of interest: energy use and IAQ. To assure whole-building performance, it is also necessary to consider the relationships between metrics for interacting components and systems (Koles et al., 1996). For example, house size and airtightness, mechanical ventilation airflows, and pollutant emission rates must be quantified to understand the impact of ventilation on energy use and IAQ. All other things being equal, increasing ventilation airflows will often improve IAQ, but will also increase energy use. Diagnostics in the form of relatively quick short-term measurements (such as measurements of mechanical airflow) and more complex analytical techniques (such as measuring a suite of indoor concentrations) can be used to evaluate such metrics. A metric quantified by diagnostics does not indicate good or bad performance. The norms will refer to the expected level of performance delivered by a system or piece of equipment. In the case of residential ventilation for new houses, Title 24 uses ASHRAE Standard 62.2 to provide norms for comparison, in the form of minimum ventilation rates.

Quantifying energy and IAQ performance is only the first step in a commissioning process. The potential *value* that commissioning provides by improving performance also needs to be evaluated. Decisions can then be made about whether or not it is cost effective to alter performance. For example, it may be possible to improve system performance simply by making minor adjustments, repairs or retrofits on the spot. Such tuning can often provide significant improvements in performance for very small marginal cost. After the tuning, there still may be components that are not performing to their desired level. In this case, a third, more involved step can provide the client with information about what potential repair or retrofit opportunities should be further investigated (e.g. sealing the interface between the garage and house), what the potential benefits will be, and at what cost.

How commissioning is performed is usually dependent on who is conducting the commissioning and for what purpose. For builders complying with ASHRAE Standard 62.2, most use a prescriptive approach. The metric in this case is code compliance. The norm is to use the prescribed fan size and ducts. The diagnostics are to confirm that the duct systems meet the prescribed requirements. Tuning only occurs if the duct and fan system are obviously not meeting the prescribed standards. Those commissioning to meet the intent of ASHRAE 62.2 tend to use a different approach. In this case, the metric is airflow rate, which is diagnosed using flow

measurement devices. The norm is meeting the ASHRAE 62.2 minimum airflow rate. Tuning would be to adjust over or under performing systems to the norm.

Literature about commissioning installed ASHRAE 62.2 systems is limited. However, the small number of studies generally focus on the metric of airflow rate and evaluate whether ventilation systems comply with ASHRAE 62.2 (Offerman, 2009b). The underlying assumption is that ASHRAE 62.2 provides the correct amount of ventilation to provide good IAQ, and that the optimal goal is to meet that requirement with as little energy as possible. The assumption of providing ventilation equivalent to that provided by an ASHRAE 62.2-compliant whole-house fan has also been used to explore alternative ventilation strategies (Sherman et al., 2011b, Mortensen et al., 2011, Sherman et al., 2011a). The decision to adjust the system would be evaluated based on meeting ASHRAE 62.2 in the most cost effective manner. Independent studies have shown that even when ASHRAE 62.2 is met in new California homes, existing health standards may not be met (Offerman, 2009b). Work by Logue et al. (2011a) has shown that more than one pollutant drive health impacts in homes.

The goal of this work is to explore the potential of using comprehensive health and energy benefits of a ventilation system to assess whether the system should be tuned. The idea being that the cost of tuning the system should be less than the potential benefits of the change. In this context, the metric would be the combined health and energy benefit due to whole-house mechanical ventilation, the diagnostics would be airflow measurements and pollutant emission rates, and the norm would be the maximum benefit for a given home. The advantage of this approach is that we will be commissioning to maximum benefit for the occupants, and not to comply with a standard alone - as this may result in a net cost to the occupants.

This approach to commissioning requires a method of combining energy and ventilation-related health impacts. In the outdoor environment, studies have used a health impact approach to aggregate the costs and benefits of energy related policies. Gilmore et al. (2006) aggregated the health costs and energy benefits of using diesel generators to offset peak electricity use in New York. The US Environmental Protection Agency used an impact

assessment approach to quantify the health benefits and regulation costs of the Clean Air Act (EPA, 1999). We applied a similar methodology to the indoor environment to quantify the costs and benefits of commissioning mechanical ventilation systems indoors.

In this study, we used computer simulations to compare and combine energy and IAQ benefits/costs of whole-house ventilation systems for a set of modeled houses representative of new California homes. We compared homes that met the norm of ASHRAE Standard 62.2 to those that under- and over-ventilate in comparison to the standard. The results were used to assess the potential benefits of commissioning, to suggest diagnostics for commissioning, and to estimate a range of costs that would be acceptable for commissioning and repair of new and existing whole-house ventilation systems. The following describes our assessment approach, simulations, and results.

2. APPROACH

To demonstrate the potential value of commissioning residential ventilation systems, we used computer simulations to assess energy use and IAQ for new homes in California over a range of climate zones. We focused on faults that might occur in two common whole-house mechanical systems: (1) a whole-house exhaust fan and (2) a heat recovery ventilator (HRV). The system faults caused either under-ventilation and reduced IAQ, or over-ventilation and increased energy use. The energy and IAQ impacts were converted to a monetary value using a Time Dependent Valuation (TDV) approach for energy and a Disability Adjusted Life Year (DALY) impact assessment approach for IAQ. We then combined the monetary impacts over a 30-year period to represent the net present value (NPV) of the fiscal cost/benefit to the endpoint user (not including the actual cost of commissioning).

It should be noted that that under- and over-ventilation are not absolute concepts. Codes and standards such as ASHRAE 62.2 set guideline minimum ventilation rates that, due to individual occupant perception of IAQ and the diversity of indoor air contaminants, do not necessarily guarantee good IAQ over the entire population (ASHRAE, 2010).

Residential Energy and Airflow Modeling

To perform the simulations, we used REGCAP - LBNL's in-house residential building energy and ventilation simulation tool with mass, heat, and moisture transport models (Walker et al., 2006). A key aspect of the REGCAP is that it explicitly includes all the HVAC system related airflows including duct leakage and grille flows. The airflows include the effects of weather and leak location, and the interactions of HVAC system flows with house and attic envelope tightness. For this analysis, we used REGCAP to determine the HVAC system energy use and air exchange rates of a set of representative homes on a minute-by-minute basis for a calendar year. Appendix B provides further information about the REGCAP model.

We simulated three houses typical to California (see Table 1) with various ventilation system malfunctions that could be identified or rectified by commissioning. The three houses had occupied floor areas of 111 m^2, 195 m^2 and 250 m^2 (1,200 ft^2, 2,100 ft^2 and 2,700 ft^2 respectively) and were based on CEC Title 24 housing prototypes (Nittler and Wilcox, 2008, CEC, 2008a).

Table 1: Simulated building characteristics

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

We modeled each house in three California climate zones: Oakland (CZ3, coastal), Sacramento (CZ12, hot) and Mount Shasta (CZ16, cold) as defined by the CEC (2008b). Weather data files used were the Title 24 compliant TMY3 hourly weather data files (Wilcox and Marion, 2008) published by NREL. These were converted to minute-by-minute format by linear interpolation for use in REGCAP.

Building insulation levels were taken from the CEC Alternative Calculation Method (CEC, 2008a). Heating and cooling equipment was sized from Rick Chitwood's unpublished field survey of Californian homes (Chitwood, 2011) undertaken in support of Title 24. Auxiliary ventilation was simulated in the form of intermittent use of bathroom, kitchen range hood and

clothes dryer exhausts. These devices were operated with predetermined schedules to simulate typical usage.

Moisture generation rates were based on ASHRAE Standard 160 (ASHRAE, 2009) with corrections for kitchen and bathroom source moisture removal from Emmerich et al. (2005). Appendix C provides further details about the modeled homes.

Whole-House Ventilation Systems

Two whole-house ventilation systems were studied: (1) whole-house exhaust ventilation and (2) Heat Recovery Ventilation (HRV). For ASHRAE 62.2, whole-house mechanical ventilation is sized as follows:

$$\begin{aligned} Q(L/s) &= 0.05 A_{floor}\left(m^2\right) + 3.5(N+1) \\ Q(cfm) &= 0.01 A_{floor}\left(ft^2\right) + 7.5(N+1) \end{aligned} \tag{1}$$

Where: Q = minimum required whole-house airflow rate [L/s and cfm]

N = number of bedrooms in the house [-]

Whole-House Exhaust Only

The ASHRAE 62.2 minimum airflow rate was used as a baseline for normal operation of the mechanical whole-house exhaust. The airflow rate was then simulated at 25, 50, and 75% of the 62.2 airflow rate to model underperforming ventilation strategies with inadequate airflows. Airflow rates of 200 and 300% of the ASHRAE 62.2 rate were also simulated to model malfunctioning intermittent fans to determine if there were any advantages or disadvantages to over-ventilation compared to the 62.2 minimum. All whole-house fans operated continuously for 24 hours per day, 7 days per week.

HRV

A balanced and standalone (not integrated into the central forced air heating and cooling system) HRV system was simulated as a baseline. The HRV was sized to twice the ASHRAE 62.2

airflow rate and operated for the first 30 minutes of every hour. Airflow restrictions were then applied to the supply side of 50% and 100% to simulate blockages in the HRV ducts or supply registers. For the 100% blocked case (0% supply side airflow rate), there was no heat exchange with the incoming and outgoing ventilation air. Typical HRV units were selected from the HVI directory (2011) to obtain Apparent Sensible Effectiveness (ASE), power draw, and airflow rate.

Determining Indoor Contaminant Concentrations and Occupant Exposures

Whole-house ventilation systems are designed to control levels of continually emitted indoor pollutants, such as those released from materials in the home and those related to occupants and their activities. Task ventilation is intended to control episodically emitted contaminants such as cooking. Because this analysis is focused on commissioning the airflow rates of whole-house ventilation systems, we only considered the impact on controlling the continuously emitted pollutants of interest. (Logue et al., 2011a) determined that three pollutants are the dominant contributors to the chronic burden of indoor health: formaldehyde, acrolein, and particulate matter with an aerodynamic diameter of less than 2.5 microns ($PM_{2.5}$). Formaldehyde and acrolein are emitted by materials, combustion, and cooking. $PM_{2.5}$ sources include combustion (cooking, candle burning etc.), activities such as cleaning, and infiltration through the building envelope from outdoor sources. Secondhand tobacco smoke is also a major source of $PM_{2.5}$ and acrolein. This work is focused on determining the cost effectiveness of commissioning the airflow rates of whole-house ventilation systems alone and so $PM_{2.5}$ was not considered. However, it is important to note that increasing whole-house ventilation rates brings in more outdoor air. If the outdoor $PM_{2.5}$ concentration is high relative to the indoor concentration, the health burden indoors could potentially be increased. Steps must be taken to ensure that air being brought into the home is of good quality. In some homes, this may require filtering incoming air. For the purpose of this analysis, we are not considering the intake of $PM_{2.5}$ into the home due to outdoor concentrations.

For each REGCAP model run, we calculated indoor concentrations over the course of a year as a function of building air change and pollutant emission rates using a simple time-step mass balance approach. Assuming uniform concentrations throughout the home, the rate of change of concentration for continually emitted indoor contaminants is:

$$\frac{dC_{in}}{dt} = \frac{S}{V_{house}} - AC_{in} - kC_{in} + pAC_{out} \tag{2}$$

Where:

$C_{in/out}$	=	indoor or outdoor concentration [μg/m^3]
S	=	contaminant emission rate [μg/h]
V_{house}	=	building volume [m^3]
A	=	air exchange rate [1/h] (taken from REGCAP modeling results)
k	=	first order loss rate [-]
p	=	penetration coefficient [-]

We assumed a first order loss rate of zero for formaldehyde and 0.0935 per hour for acrolein (Seaman et al., 2007). The penetration coefficient is assumed to be 1 for the pollutants being modeled in this study. The discretized form of Equation (2) for pollutant, *j*, at time step, *i*, is:

$$C_{j,i} = C_{j,i-1}e^{-(A_i+k)\Delta t} + \frac{\left(S_j / V_{house} + A_i C_{j,out}\right)\left(1 - e^{-(A_i+k)\Delta t}\right)}{(A_i + k)} \tag{3}$$

A time step, Δt, of 1 minute was found to be sufficient to keep the calculations stable. For each run, initially $C_{j,i=0}$ was set to the outdoor concentration, and the first month of results was discarded as 'spin-up' time after which a full year of simulations was completed. Spin-up time is the time it takes for the model to reach dynamic equilibrium and to eliminate the effect of the initial conditions on the solution. For each home, we overlaid a weekly occupancy profile on the indoor concentration profile to determine the annual average exposure concentration for each occupant in each modeled home. In particular, we assumed that occupants were absent from 8 a.m. to 4 p.m. weekdays and present at all times over weekends.

For each of the three homes in each of the three climate zones, we simulated the indoor concentrations of formaldehyde and acrolein with three levels of pollutant loading (low, medium and high). Formaldehyde emission rates were derived from measurements taken by Offerman (2009a) who measured 24 hour average indoor and outdoor concentrations and air exchange rates for 107 new homes in California. The acrolein emission rates were derived from the acrolein measurements by Seaman et al. (2007). The 5th, 50th, and 95th percentile emission rate

values from each of the data sets were used as the low, medium, and high emission rates (see Table 2).

The outdoor concentrations (also Table 2) were taken from the National Air Toxics Assessment (NATA) 2002 modeling results (EPA, 2005). NATA modeled annual average outdoor air concentrations of air toxics on a census tract level for the United States. For each climate zone modeled in this study, the average outdoor concentrations of the county containing the representative city was used (CZ3: Alameda, CZ12: Sacramento, CZ16: Placer).

Table 2: Emission rates (ER) for formaldehyde and acrolein with outdoor concentrations (Offerman, 2009a, Seaman et al., 2007, EPA, 2005)

Pollutant	Emission Rate, ER [μg/(h m^2)]			Outdoor Concentration [μg/m^3]		
	Low ER	Medium ER	High ER	CZ 3	CZ 12	CZ 16
Formaldehyde	9.7	30.3	88.2	2.9	2.9	3.0
Acrolein	1.3	1.9	6.1	0.08	0.08	0.07

It should be noted that the analysis of acrolein and formaldehyde emission rates is complicated due to episodic and intermittent indoor sources and time-varying emission from materials. Episodic sources of acrolein and formaldehyde (i.e., cooking and indoor combustion) could increase concentrations temporarily above acute standards. These time varying effects were not included in this study.

In this report we use a simple box modeling approach to estimate concentrations. Chemical storage and source depletion were not considered. In the case of formaldehyde, more advanced models have been developed that incorporate these effects. Sherman and Hult (2012) presented a review of these models and the estimated impact of ventilation on concentrations and exposure. We did not apply these models here because two key parameters of material loading and the coupling time constant for the storage medium (*KL*), are not well established for homes. However, the work of Sherman and Hult allows us to explore the potential error introduced due to the use of our simplified model. According to the Sherman and Hult there are two main issues to address when comparing the models: the instantaneous impact of ventilation changes and the long-term source depletion. Their work indicates that when *KL* is small relative to the range of possible values and the source depletion timescale is long relative to the 30-year analysis performed here, the two modeling approaches should give equivalent results for both the total

exposure and the time varying concentration. When *KL* is large and the source depletion scale is long, the simple box modeling approach will initially underestimate the concentration by overestimating the instantaneous impact of ventilation. However, as the source depletes the simple box model will eventually overestimate the concentration. In this case the long-term exposure estimates will agree for both models but the instantaneous concentration estimates will not. If source depletion is short relative to the 30-year analysis done here, then the simple box model will predict higher long-term exposure.

Park and Ikeda (2006) measured formaldehyde concentrations for new and old homes. Concentrations in new homes decreased quickly, representing an initial off-gassing phase. Afterwards the homes reached equilibrium when formaldehyde concentrations stabilized. This seemed to indicate that after the initial off-gassing, the source depletion time scale is relatively long. There is some uncertainty as to whether we are estimating the instantaneous concentration well because KL is not well established for new homes, but that we are likely estimating the long-term exposure well using the box model approach. Applying discounting to the health benefits (discussed below) may result in their overemphasis because we are overestimating the impact of ventilation impact in the early years of the analysis.

Monetization of Energy and IAQ Benefits and Costs

Two independently derived methods were used to convert both the energy and IAQ impacts into US dollar currency - TDV and DALY. This was to allow a direct comparison between the two.

Time Dependent Valuation (TDV) of Residential Energy Use

'Peak energy demand' refers to the time of day when loads on the gas and electricity distribution grids reach a maximum. During the winter months, this is usually between 4 a.m. and 8 a.m. when external temperatures are at their coldest and consequently the heating demand is greatest. During the summer months, the demand reaches a maximum between approximately 2 p.m. and 6 p.m. when the cooling demand is greatest and consequently the air conditioning load is greatest. During these peak periods, the extra demand on the grid is met by increasing overall capacity via the operation of auxiliary power plants with a higher marginal cost. This increases the generation cost of each kilowatt-hour for the utility company which is then passed down to the consumer.

TDV is an attempt by the CEC to more preferentially weight energy saved during peak periods while the distribution grid is operating at or close to capacity (Architectural Energy Corp., 2011). The assigned weight is dependent on several factors: climate, time of energy use, building type (residential or commercial), and type of fuel (natural gas, electricity or propane).

TDV factors are given in units of energy (kBtu/kWh) and can be converted to NPV in 2011 US dollars based on 30 years of operation using a conversion factor of 0.1732 (with units of $/TDV kBtu) for low-rise residential buildings. A 3% real, inflation-adjusted discount rate was used to forecast the gas and electricity rates over the 30 years. The TDV factors can be used for cost analysis of energy saving measures implemented in new and retrofitted buildings. The energy costs do not include the externalities associated with energy production such as greenhouse gas emissions and pollutant emissions associated with energy generation.

For the purposes of this work, the electricity and gas TDV factors for California climate zones 3 (Oakland), 12 (Sacramento), and 16 (Mount Shasta) were applied to the hourly energy use of the HVAC equipment (output from the REGCAP simulations). The gas TDV factors were used for the heating furnace and the electricity factors were used for the air handler unit, mechanical ventilation, and cooling systems. This gave us the monetary cost or gain over a 30-year period for the different ventilation scenarios.

Disability Adjusted Life Year (DALY)

DALYs are a measure of overall disease burden and incorporate both disease likelihood and severity (Murray and Lopez, 1996a, Murray and Lopez, 1996b). DALYs are reported as the equivalent number of years lost from premature death and disability. They offer a way to compare mortality and morbidity. To determine the total number of DALYs lost due to changes in exposure per year, we used the impact assessment methodology developed by Huijbregts et al. (2005). They computed expected ranges of human damage and effect factors for the cancer and non-cancer chronic effects of 1,192 substances, applying equal weightings for a year lost independent of age (i.e., zero discounting). Using these values, the DALYs lost for one person breathing pollutant *j*, for one year, based on exposure and concentration were calculated using:

$$\Delta DALY_j = \frac{\partial D_j}{\partial Intake_j} \cdot \Delta Intake_j \tag{4}$$

$$\Delta DALY_i = \sum_{i=1}^{i=1\,year} \Delta C_{exposure,j} \cdot V_B \cdot \left(\frac{\partial D_{j,non-cancer}}{\partial Intake_j} + \frac{\partial D_{j,cancer}}{\partial Intake_j} \cdot ADAF \right) \tag{5}$$

Where: $\frac{\partial D_j}{\partial Intake_j}$ = cancer and non-cancer mass intake-based damage factors

$\Delta C_{exposure,j}$ = change in the indoor concentration

V_B = volume of air breathed in the residence each year [m^3]

$ADAF$ = Age-Dependent Adjustment Factor for cancer exposure as specified by the EPA (2005).

Logue et al. (2011b) determined US population average values for breathing rate (14.4 m^3/day) and ADAF (1.6). This formulation assumes that the damage-intake relationship is linear in the range of interest: from intake at concentrations resulting from ventilating at the ASHRAE 62.2 minimum rate, to concentrations resulting from ventilating at various rates due to system malfunction.

For each chemical, Huijbregts et al. (2005) presented both a central estimate and the estimated uncertainty of the mass intake-based damage factors. Uncertainty was assumed to be lognormal and characterized by a factor, *k*, equal to:

$$k = \sqrt{\frac{97.5th\ percentile}{2.5th\ percentile}} \tag{6}$$

This includes the aggregated uncertainty of the rate of disease incidence, as well as the uncertainty in the damage per incidence of disease. A Monte-Carlo simulator was used to develop a distribution of aggregate health damage for chronic pollutant intake via indoor air that propagated the uncertainty in the health damages. The annual IAQ damage for each home was assumed to be the median value of the distribution. The model was run a sufficient number of times to yield stable mean and standard deviations for the damage for each home.

To determine the NPV of changes in exposure for each simulation for 30 years (to allow comparison with the 30-year TDV energy NPV), we determined the annual cost of DALYs lost

or gained relative to a system that was operating at the level specified by ASHRAE 62.2. The projected value for each DALY is of the order of US $50,000 to $160,000 (Brown, 2008, Lvovsky et al., 2000). For this project, we assumed a central cost of $100,000 per DALY lost in 2011 US dollars. There is no consensus as to the appropriate discount rate for future health benefits. Krupnick (2004) reviewed the policy choices of valuing health outcomes. According to Krupnick, many economists have concluded that there is no basis for discounting health benefits the same as cost and doing so, given the long-term benefits of health impacts, could lead to important health policies being overlooked. Krupnick also indicated that several European countries are mandating that economic assessments either do no discounting, or use a lower discount rate than for costs. In this analysis, we applied a discount rate of 3%, the same discount rate applied to the energy analysis. This may be considered to be at the higher end of acceptable discount rates for health analysis. However, using the same discount rate equally values the future energy and health benefits.

3. RESULTS AND DISCUSSION

Results below are presented and discussed for the health and energy impacts of commissioning whole-house ventilation rates, and the implications of this study on optimizing whole-house ventilation rates.

Commissioning Whole-House Ventilation Rates

The energy components are dominated by the space-conditioning load and so are dependent on climate and house size. The health components are dependent on the ventilation rate, which scales with house size and number of occupants, and is independent of climate. However, the health components dominate the energy components so the results between the different house sizes and climate zones show insufficient variability to justify independent discussion. As a consequence, the results may be applied to other regions and countries, not just California. The discussion will present results only for the medium sized house (195 m^2) in Sacramento (climate zone 12). Results for the other houses and climate zones are provided in Appendix A.

Combining the DALY dollar cost associated with IAQ, with the TDV dollar cost associated with energy use, allowed us to show the dollar cost or benefit over 30 years from commissioning to fix a malfunctioning whole-house ventilation system so that it complies with Standard 62.2. All of the monetary results presented here are for the NPV of the 30-year health benefits and energy costs for a single model home in 2011 US dollars. The NPV values are the difference between the malfunctioning systems and the norm i.e., a system operating as specified by ASHRAE 62.2.

The ASHRAE 62.2 whole-house minimum mechanical ventilation airflow rates (from equation 1) are 20, 24 and 30 L/s [42, 51 and 65 cfm] for the prototype B, C and D houses respectively. Figure 1 shows the breakdown between the energy and the IAQ components for ASHRAE 62.2 ventilation rates of 0, 25, 50, 75, 100, 200 and 300%. Figure 2 demonstrates the combined energy and IAQ NPV. A positive dollar value represents money saved (benefit) while a negative dollar value represents money lost (cost, or negative benefit).

The 100% ASHRAE 62.2 ventilation rate was taken as the norm to which the other ventilation rates were compared. Under-ventilation represents an energy benefit from reduced mechanical ventilation energy and reduced heating and air conditioning loads, and an IAQ cost from higher contaminant levels. Conversely, over-ventilation represents an energy cost from higher fan energy use and increased space conditioning loads, and an IAQ benefit from reduced contaminant levels.

Results for the 195 m^2 house in Sacramento

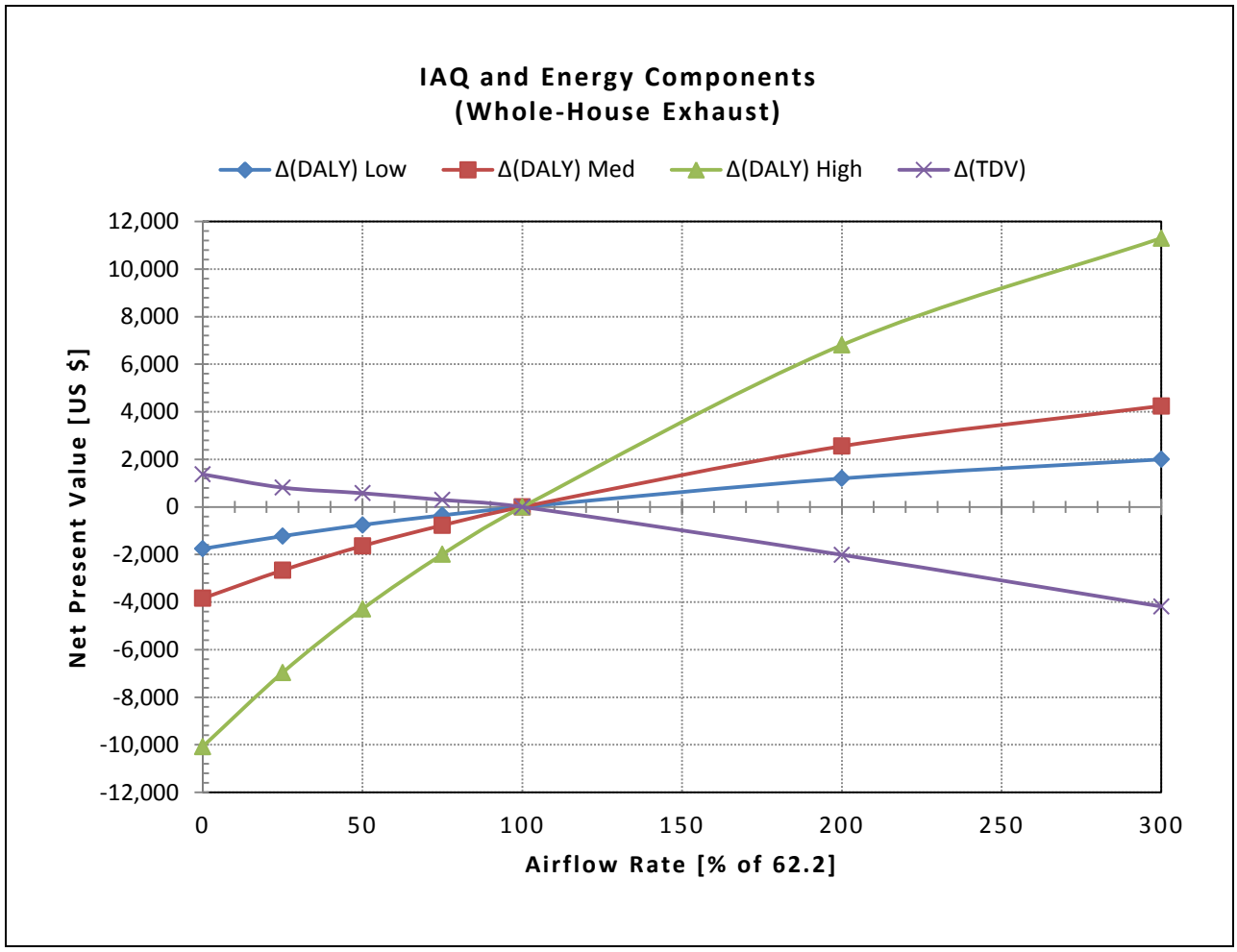

Figure 1: IAQ and energy components, relative to 100% ASHRAE 62.2 airflow rate for 30-year NPV of commissioning a malfunctioning whole-house exhaust for three contaminant emission rates (low, med and high). 100% is equal to 24 L/s [51 cfm]. Results are for the 195m^2 house in Sacramento

As an example, consider the 50% ASHRAE 62.2 ventilation rate case (this is a whole-house exhaust fan underperforming and so delivering only half the 62.2 ventilation rate) from Figure 1. The TDV energy financial benefit is $576 over 30 years. This represents money saved on energy bills due to the decreased ventilation rate. For the medium contaminant emission house with the same 50% airflow rate, the IAQ financial benefit is negative $1,639 over 30 years. This represents money lost (or cost) due to reduced air quality from exposure to indoor contaminants. When the energy and IAQ costs are combined in Figure 2, the net benefit is negative $1,063, which represents an overall loss (the financial value of the energy saved is less than the financial value of life lost due to higher contaminant levels).

The worst case is a non-functioning (0% of the 62.2 airflow rate) whole-house exhaust system in the high emission house. This will cost the occupants approximately $8,700 net over 30 years. Over ventilating the same high emission house with an airflow rate of 300% the 62.2 minimum will gain the occupant approximately $7,100 net (a $15,800 difference). In the latter case, fixing the system to meet the norm (ASHRAE 62.2) would actually be detrimental to the occupants as the value of the energy saved from reducing the system airflow rate is vastly outweighed by the benefit from improved IAQ.

The cost to the occupants of the low emission house with a non-functioning whole-house exhaust system is approximately $390 which is comparatively small over a 30-year time period. The low emission house also sees a net loss of $2,200 from over ventilating by 300%, due to increased energy consumption. In both cases, repairing the system to meet the norm would be beneficial.

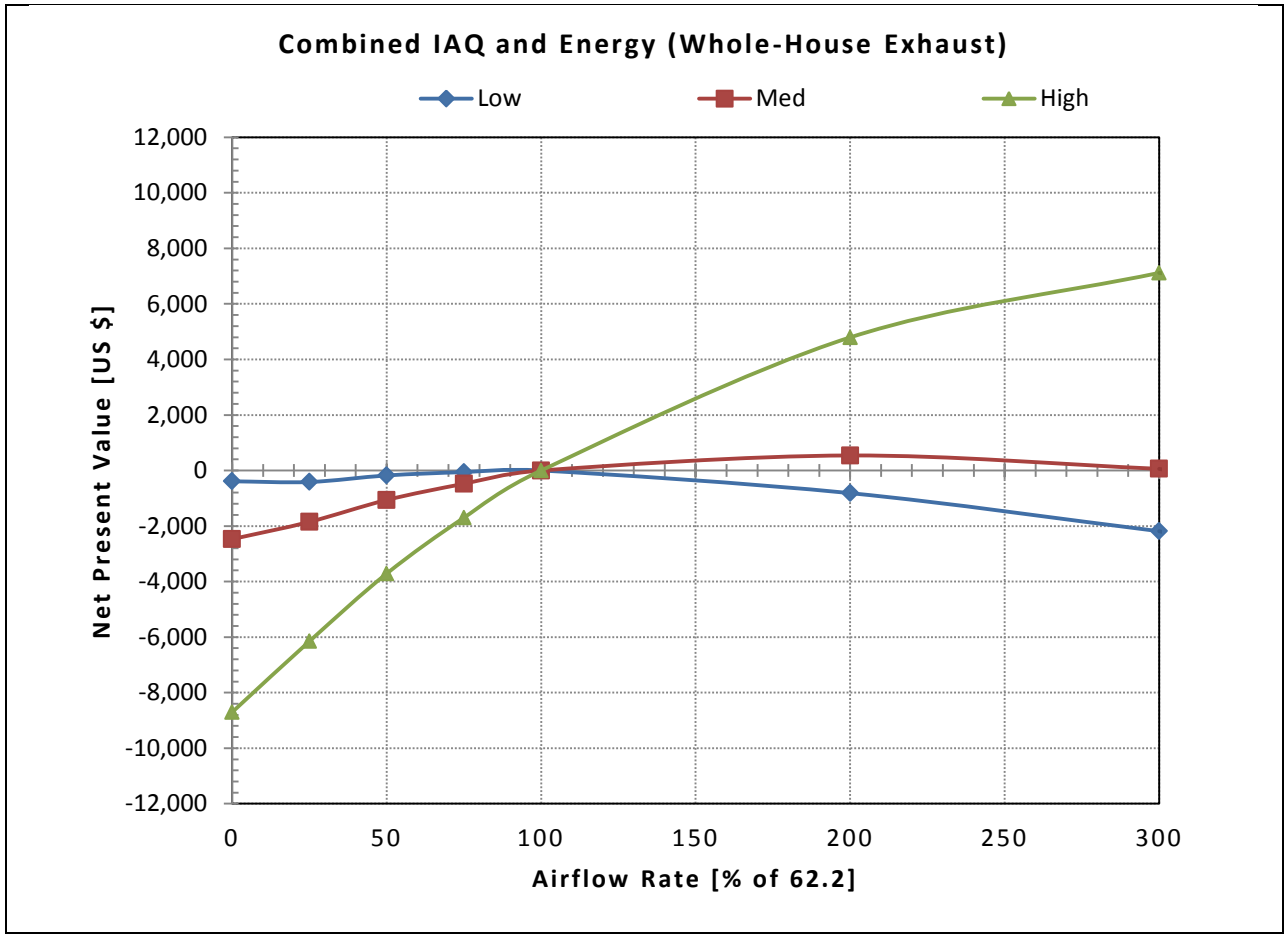

Figure 2: Combined IAQ and energy benefit from commissioning a malfunctioning 62.2 whole-house exhaust for three contaminant emission rates (low, med and high)

Figure 3 shows the 30-year dollar benefit from commissioning a malfunctioning HRV system with 0, 50 and 100% supply side airflow. Figure 4 shows the combined energy and IAQ components. Again, results are for the 195 m^2 house in Sacramento. The 100% supply side airflow case was used as a baseline. Zero and 50% supply side airflow increase the TDV estimated energy cost due to reduced heat exchange between incoming and outgoing air, thus increasing the building heating load. The DALY estimated health cost also increases due to reduced building air exchange rates (and higher indoor contaminant levels) from the imbalance in mechanical ventilation.

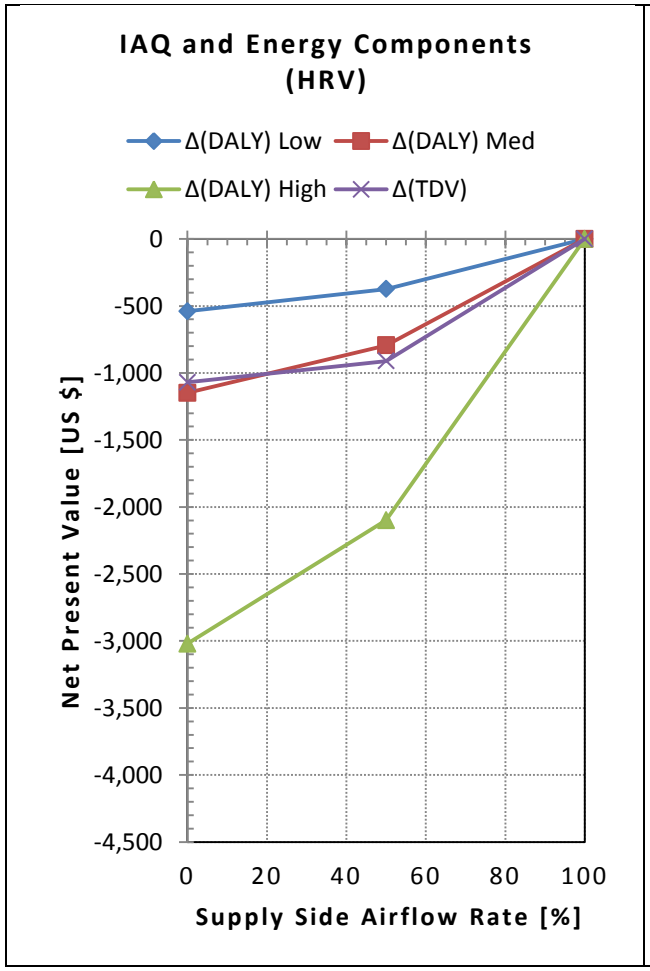

Figure 3: IAQ and energy components for the 30-year NPV of commissioning a malfunctioning HRV system for three contaminant emission rates (low, med and high)

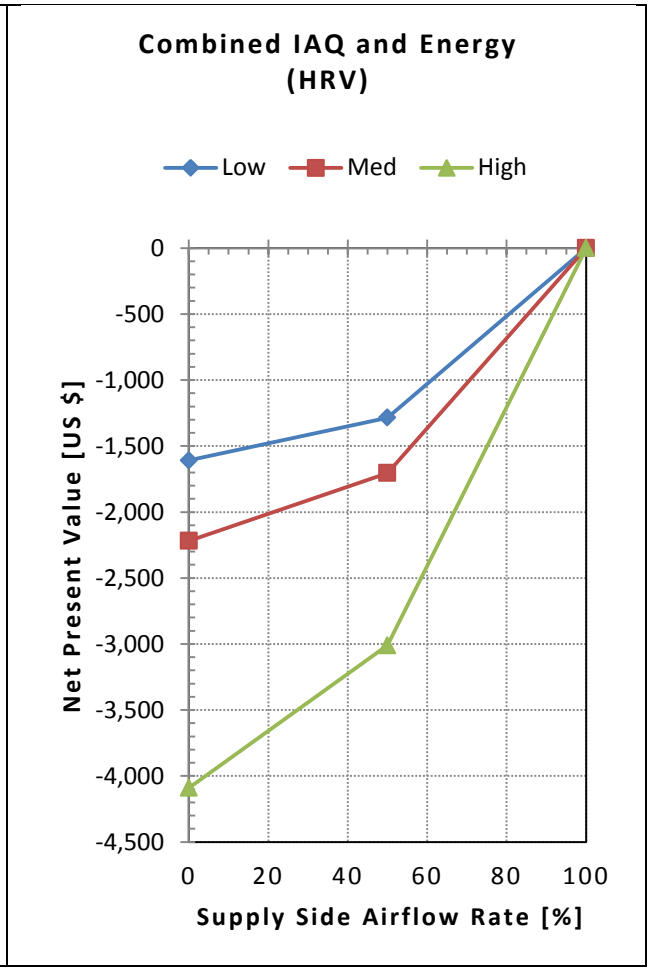

Figure 4: Combined IAQ and energy components for the 30-year NPV of commissioning a malfunctioning HRV system for three contaminant emission rates (low, med and high)

There is no positive financial benefit to be had from an HRV system with blocked filters or supply registers, relative to an HRV that opperates as specified by ASHRAE 62.2. A benefit

might be seen if the HRV were to operate for longer than the intended time period each hour, but this was not simulated. Commissioning a blocked HRV would always be worthwhile provided that the cost of commissioning is less than the combined cost of the energy used and life lost over 30 years (or some other acceptable payback period to the occupant).

Results for both whole-house exhaust fan and HRV systems are highly dependent on the continuous contaminant emission rates. In medium and high emission homes, commissioning could play a vital role in improving IAQ where whole-house ventilation systems are not providing adequate airflow rates. Over 30 years, the health benefit in 2011 US dollars from ventilating properly vastly outweighs the energy benefit from under-ventilating. However, when the malfunction is providing over-ventilation in medium and high emission homes (i.e., the malfunctioning intermittent whole-house fan operating for longer time periods), an airflow-only based commissioning process could actually be detrimental to the occupants because fixing the malfunction would reduce the mechanical ventilation airflow rate and increase the health costs. This suggests that commissioning processes for whole-house ventilation systems should include both energy use and IAQ as metrics. The results also suggest that controlling and limiting the levels of continuous contaminant emissions may also be an important tuning tool for residential ventilation systems. Labeling schemes now exist for products that meet low emission standards, such as California Section 01350 (CDPH, 2010). The commissioning process could involve the practitioner looking for labeled products in the house to help quantify the levels of continuous emissions.

The ideal scenario would be a commissioning process that requires the proper diagnostic measures to determine the total energy and IAQ cost or benefit for a given home as a function of system air flow rate, followed by identification of the tuning options for that home, cost analysis of those options, then finally the implementation of those options dependent on the cost benefit to the home owner.

Commissioning is performed in steps, and whether or not to perform each step should be evaluated along the way. From the homes studied here, the first step of performing diagnostics appears to be justified in the majority of new homes. For low emission homes, under the assumption of the proper use of task ventilation, tuning the airflow rate will always be of value

so long as the price of tuning is less than the 30-year health and energy cost of an over-ventilating system. Currently it would be difficult and potentially costly for a commissioning professional to perform the diagnostics required to estimate the household continuous emission rates of the pollutants of concern, especially as these are subject to change based on occupants and their behavior.

A comprehensive set of building analysis tools and policies are needed to strike a balance between building energy use and IAQ. There has been a national move toward more energy efficient buildings. A major limit to reducing building energy demand for health and cooling is providing sufficient ventilation for the building occupants. Setting ventilation standards to meet all outdoor air quality standards is likely to be prohibitively expensive. Meeting California OEHHA (Office of Environmental Health Hazard Assessment) reference exposure levels would require an air exchange rate of 0.5 air changes per hour (Sherman and Hodgson, 2004). The European Union has looked into developing the methods needed to broadly explore the energy and IAQ trade-off (de Oliveira et al., 2004). The Lawrence Berkeley National Laboratory is currently in the process of conducting research to aid the development of health-based ventilation standards for the US residential housing stock that considers both health and energy impacts (Logue et al., 2011c). In addition to health-based standards, metrics for commissioning are needed that consider health. The purpose of this report was to demonstrate one method of commissioning whole house ventilation systems that takes into account IAQ health impacts as well as energy. The calculated benefits of tuning can be compared to the costs of commissioning to decide if any action should take place. Potentially the cost can be calculated based on the status of the home - whether it is at the building stage or if it is an existing home suitable for retrofit. The current work takes into account total occupancy. In home applications, such as during asset tagging, the commissioner can provide the health benefit per person and energy penalty for the house so that occupancy changes can be taken into account when assessing tuning.

Ventilation Rate Optimization

As a result of combining IAQ and energy costs, it is also possible to attempt to optimize the ventilation rate to find the most cost-effective level of IAQ. Figure 5 shows the 30-year absolute NPV in US dollars once the IAQ and energy values have been combined.

Assuming a binomial relationship, the curves in Figure 5 have been extrapolated past the 300% ASHRAE 62.2 airflow rate that was modeled. As the ventilation rate increases the NPV decreases due to lower indoor contaminant concentrations. At higher airflow rates energy costs begin to dominate and cause the NPV to increase. The optimum ventilation rates are at the local minima, or where the differentials of the curves are equal to zero. For the high emission house the optimum airflow rate was approximately 310% of the 62.2 minimum. For the medium emission house it was around 200%. For the low emission house the optimum ventilation rate was approximately 85% of the 62.2 minimum. So for the medium and high emission houses these results suggest that the minimum ASHRAE 62.2 airflow rate was not high enough for the particular house that was modeled. For the low emission house the minimum 62.2 airflow rate was slightly too high suggesting over-ventilation.

This approach is highly dependent on emission rates, but the high and low emission rates used in this study should act as boundary conditions. Further work will be needed to apply this method to ventilation standards such as ASHRAE 62.2.

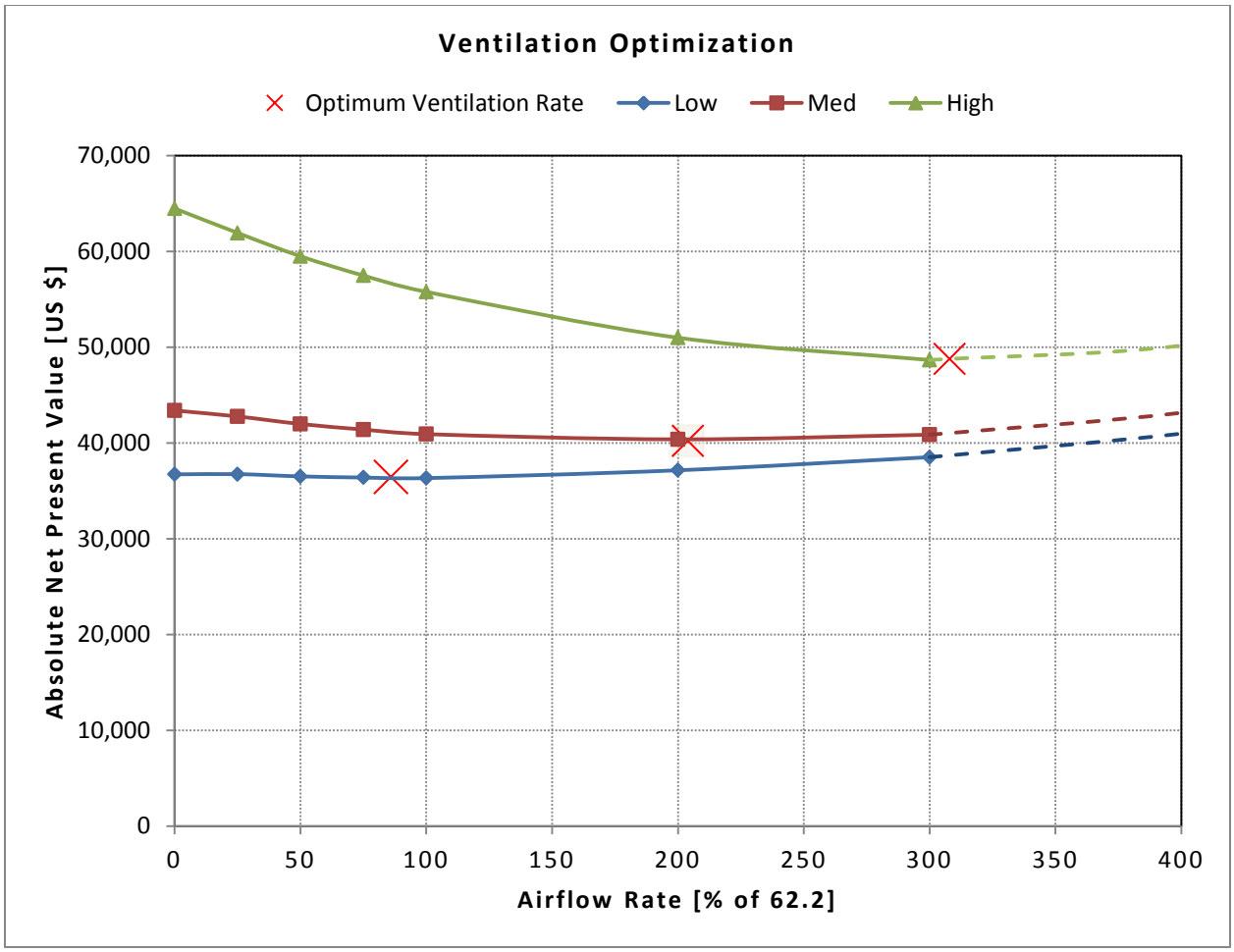

Figure 5: Optimization curves for IAQ and energy showing the absolute NPV values. The local minima are the points representing the minimum cost to the occupants. Dashed lines show the extrapolated curves

4. CONCLUSIONS AND RECOMMENDATIONS

Our results show that health benefits dominate over energy benefits when converted to US dollars using DALY and TDV approaches. This was independent of house size and climate. The potential health impacts were large when ventilation rates were insufficient to dilute the emitted indoor contaminants. Providing minimum airflow rates to comply with ASHRAE Standard 62.2 alone is not a sufficient metric for commissioning whole-house ventilation systems and ideally, decisions about tuning should be made with knowledge on indoor pollutant emission rates, ventilation airflow rates, and outdoor air quality. The metric should be NPV of the combined energy and IAQ benefits to the consumer and commissioning cost decisions should be made relative to that value even if that means ventilating to exceed the ASHRAE 62.2 minimum. Identifying that diagnostics are needed to quantify emission rates will hopefully spur industry to develop an appropriate tool for the commissioning community. Identification of low emission products contained within the home via labeling schemes could be part of the commissioning process. As a consequence of combining energy costs with monetized IAQ costs we now have the beginnings of an approach to optimize the ventilation rates of homes.

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Appendix A: Further Results

Below is the breakdown of the energy consumption figures and household air change rates for the medium house in Sacramento for the whole-house exhaust (Table 3) and the HRV (Table 4). Table 5 reports the mean and peak hourly concentration of formaldehyde and acrolein.

Table 3: Whole-house exhaust, energy consumption for the HVAC systems with varying airflow rates (medium house, CZ12 Sacramento). 100% was used as the baseline for the TDV and DALY calculations

Fan Airflow Rate [% of 62.2]	Air Handler [kWh]	Heating [kWh]	Cooling [kWh]	Mechanical Ventilation [kWh]	Total [kWh]	Average ACH [/h]
0	605	16,639	1,201	25	18,470	0.2
25	610	16,931	1,187	115	18,842	0.23
50	614	17,228	1,173	115	19,130	0.25
75	620	17,539	1,162	115	19,435	0.27
100	626	17,854	1,155	115	19,750	0.3
200	657	19,409	1,119	265	21,450	0.44
300	699	21,479	1,088	300	23,565	0.61

Table 4: HRV, energy consumption for the HVAC systems with varying blockages to the supply side airflow rate (medium house, CZ12 Sacramento). 100% supply airflow was used as a baseline

Supply Airflow Rate [%]	Air Handler [kWh]	Heating [kWh]	Cooling [kWh]	Mechanical Ventilation [kWh]	Total [kWh]	Average ACH [/h]
100	613	17,229	1,159	524	19,525	0.41
50	632	18,149	1,146	524	20,451	0.37
0	635	18,355	1,138	524	20,653	0.35

Table 5: Summary statistics for the small home with whole-house ventilation at the level specified by ASHRAE 62.2 in climate zone 3.

Formaldehyde Concentrations [µg/m^3]	Emission Rate of Home		
	Low	Medium	High
Annual Mean	16.5	45.3	98.4
Peak hourly	23.3	66.5	146.1
Hours exceeding acute standard	0%	14%	98%
Acrolein Concentrations [µg/m^3]	**Low**	**Medium**	**High**
Annual Mean	1.5	2.1	6.5
Peak hourly	2.0	2.8	8.8
Hours exceeding acute standard	0%	10%	100%
Chronic Damage [DALYs/100,000 people/year]	**Low**	**Medium**	**High**
Central Estimate	59.6	114.9	298.7
Lower Bound 95% Confidence Interval	2.6	5.8	13.9
Upper Bound 95% Confidence Interval	7054	9460	31201

Table 6: Whole-house exhaust simulation results for all house sizes and climate zones

CZ	House Size	Q [%]	Annual Energy [kWh]	ACH [/h]	TDV [$]	DALY LOW [$]	DALY MED [$]	DALY HIGH [$]	Δ(TDV) [$]	Δ(DALY) LOW [$]	Δ(DALY) MED [$]	Δ(DALY) HIGH [$]	TDV & DALY LOW [$]	TDV & DALY MED [$]	TDV & DALY HIGH [$]
3	111.5	0.0	11,663	0.22	12,853	6,465	13,054	33,918	1,572	-2,330	-5,057	-13,297	-758	-3,485	-11,725
3	111.5	25	12,044	0.26	13,456	5,699	11,388	29,547	969	-1,564	-3,391	-8,926	-596	-2,422	-7,958
3	111.5	50	12,353	0.29	13,758	5,094	10,059	26,066	667	-959	-2,063	-5,445	-292	-1,396	-4,778
3	111.5	75	12,674	0.33	14,079	4,596	9,000	23,262	347	-461	-1,003	-2,641	-114	-656	-2,295
3	111.5	100	13,027	0.38	14,425	4,135	7,997	20,621	0	0	0	0	0	0	0
3	111.5	200	14,939	0.62	16,546	2,768	5,115	12,930	-2,121	1,367	2,882	7,690	-754	761	5,570
3	111.5	300	16,941	0.87	18,880	2,131	3,787	9,385	-4,455	2,004	4,210	11,236	-2,451	-245	6,781
3	195.1	0	19,696	0.18	21,465	7,154	14,572	37,881	1,853	-2,153	-4,707	-12,362	-300	-2,854	-10,509
3	195.1	25	20,134	0.21	22,145	6,463	13,053	33,948	1,174	-1,462	-3,188	-8,428	-289	-2,014	-7,254
3	195.1	50	20,521	0.23	22,535	5,890	11,800	30,632	783	-890	-1,935	-5,113	-107	-1,153	-4,330
3	195.1	75	20,881	0.26	22,900	5,410	10,756	27,893	418	-410	-891	-2,373	8	-473	-1,955
3	195.1	100	21,291	0.28	23,318	5,001	9,865	25,520	0	0	0	0	0	0	0
3	195.1	200	23,379	0.43	25,807	3,619	6,913	17,722	-2,488	1,381	2,952	7,797	-1,107	463	5,309
3	195.1	300	25,759	0.60	28,358	2,778	5,133	12,972	-5,039	2,223	4,732	12,548	-2,816	-308	7,509
3	250.8	0	25,258	0.22	28,279	7,646	15,355	39,912	2,184	-1,923	-4,157	-10,989	261	-1,974	-8,805
3	250.8	25	25,799	0.24	29,092	7,063	14,100	36,594	1,371	-1,340	-2,903	-7,671	32	-1,531	-6,300
3	250.8	50	26,236	0.27	29,522	6,557	12,997	33,683	941	-834	-1,800	-4,760	107	-859	-3,819
3	250.8	75	26,678	0.29	29,963	6,114	12,035	31,150	500	-391	-838	-2,227	109	-338	-1,727
3	250.8	100	27,169	0.32	30,463	5,723	11,197	28,923	0	0	0	0	0	0	0
3	250.8	200	29,311	0.43	32,851	4,478	8,545	21,895	-2,388	1,245	2,652	7,027	-1,143	263	4,639
3	250.8	300	32,180	0.59	36,287	2,814	6,505	16,467	-5,824	2,909	4,692	12,456	-2,915	-1,133	6,631
12	111.5	0	11,283	0.24	19,040	5,988	12,008	31,177	1,131	-1,968	-4,254	-11,205	-837	-3,123	-10,074
12	111.5	25	11,601	0.27	19,552	5,365	10,653	27,598	619	-1,345	-2,900	-7,626	-726	-2,281	-7,007
12	111.5	50	11,846	0.31	19,757	4,848	9,532	24,685	414	-828	-1,778	-4,712	-414	-1,365	-4,299
12	111.5	75	12,101	0.35	19,975	4,415	8,612	22,207	196	-395	-858	-2,235	-200	-663	-2,039
12	111.5	100	12,353	0.39	20,171	4,020	7,754	19,972	0	0	0	0	0	0	0
12	111.5	200	13,920	0.62	21,717	2,756	5,092	12,861	-1,546	1,264	2,662	7,111	-282	1,116	5,565
12	111.5	300	15,680	0.87	23,683	2,128	3,785	9,357	-3,512	1,892	3,968	10,616	-1,620	456	7,103
12	195.1	0	18,470	0.20	30,195	6,525	13,198	34,293	1,370	-1,759	-3,842	-10,074	-389	-2,472	-8,704
12	195.1	25	18,842	0.23	30,753	5,992	12,019	31,183	813	-1,226	-2,663	-6,964	-414	-1,851	-6,151
12	195.1	50	19,130	0.25	30,989	5,521	10,995	28,509	576	-755	-1,639	-4,290	-179	-1,063	-3,713

CZ	House Size	Q [%]	Annual Energy [kWh]	ACH [/h]	TDV [$]	DALY LOW [$]	DALY MED [$]	DALY HIGH [$]	Δ(TDV) [$]	Δ(DALY) LOW [$]	Δ(DALY) MED [$]	Δ(DALY) HIGH [$]	TDV & DALY LOW [$]	TDV & DALY MED [$]	TDV & DALY HIGH [$]
12	195.1	75	19,435	0.27	31,272	5,118	10,128	26,213	294	-352	-773	-1,994	-59	-479	-1,701
12	195.1	100	19,750	0.30	31,565	4,766	9,356	24,219	0	0	0	0	0	0	0
12	195.1	200	21,450	0.44	33,578	3,569	6,802	17,413	-2,012	1,197	2,554	6,806	-815	541	4,794
12	195.1	300	23,565	0.61	35,751	2,767	5,110	12,917	-4,186	1,999	4,245	11,302	-2,187	60	7,117
12	250.8	0	23,333	0.24	38,713	7,068	14,107	36,572	2,010	-1,628	-3,516	-9,256	382	-1,506	-7,246
12	250.8	25	23,806	0.27	39,462	6,589	13,065	33,866	1,262	-1,149	-2,475	-6,551	112	-1,213	-5,289
12	250.8	50	24,178	0.29	39,852	6,162	12,141	31,417	871	-722	-1,550	-4,102	149	-679	-3,231
12	250.8	75	24,592	0.31	40,286	5,778	11,315	29,268	438	-338	-724	-1,952	99	-287	-1,515
12	250.8	100	25,004	0.34	40,724	5,440	10,590	27,316	0	0	0	0	0	0	0
12	250.8	200	26,914	0.46	43,073	4,346	8,262	21,146	-2,350	1,094	2,328	6,170	-1,256	-21	3,820
12	250.8	300	29,435	0.60	46,344	2,787	6,445	16,290	-5,621	2,653	4,145	11,025	-2,968	-1,475	5,405
16	111.5	0	17,026	0.23	21,051	6,272	12,654	32,833	1,776	-2,275	-4,942	-13,000	-499	-3,166	-11,224
16	111.5	25	17,518	0.27	21,696	5,542	11,038	28,618	1,131	-1,545	-3,326	-8,786	-413	-2,195	-7,654
16	111.5	50	17,958	0.31	22,079	4,951	9,760	25,223	748	-954	-2,048	-5,391	-205	-1,300	-4,642
16	111.5	75	18,401	0.35	22,459	4,449	8,676	22,403	368	-451	-965	-2,570	-83	-596	-2,201
16	111.5	100	18,855	0.40	22,827	3,997	7,712	19,833	0	0	0	0	0	0	0
16	111.5	200	21,374	0.62	25,315	2,746	5,067	12,823	-2,488	1,251	2,645	7,009	-1,237	157	4,521
16	111.5	300	24,380	0.88	28,518	2,115	3,758	9,315	-5,691	1,882	3,954	10,518	-3,809	-1,737	4,827
16	195.1	0	28,743	0.19	34,870	6,966	14,166	36,827	2,196	-2,117	-4,633	-12,155	79	-2,436	-9,959
16	195.1	25	29,327	0.22	35,651	6,297	12,705	32,982	1,415	-1,448	-3,171	-8,310	-33	-1,757	-6,895
16	195.1	50	29,846	0.24	36,096	5,740	11,472	29,781	970	-891	-1,938	-5,109	79	-968	-4,139
16	195.1	75	30,389	0.27	36,565	5,264	10,438	27,045	501	-415	-904	-2,374	86	-403	-1,873
16	195.1	100	30,960	0.30	37,066	4,849	9,534	24,672	0	0	0	0	0	0	0
16	195.1	200	33,631	0.44	39,844	3,548	6,754	17,305	-2,778	1,301	2,780	7,366	-1,477	2	4,589
16	195.1	300	37,223	0.61	43,517	2,756	5,085	12,866	-6,451	2,093	4,449	11,806	-4,358	-2,002	5,355
16	250.8	0	38,195	0.24	46,027	7,407	14,870	38,567	2,890	-1,900	-4,141	-10,875	990	-1,251	-7,985
16	250.8	25	38,971	0.27	46,996	6,818	13,596	35,211	1,922	-1,311	-2,867	-7,518	611	-945	-5,597
16	250.8	50	39,645	0.29	47,609	6,323	12,493	32,382	1,308	-816	-1,764	-4,690	492	-456	-3,382
16	250.8	75	40,283	0.32	48,206	5,890	11,565	29,871	711	-383	-836	-2,179	328	-125	-1,468
16	250.8	100	41,029	0.34	48,917	5,507	10,729	27,692	0	0	0	0	0	0	0
16	250.8	200	44,109	0.46	52,056	4,295	8,151	20,859	-3,139	1,212	2,578	6,833	-1,927	-561	3,694
16	250.8	300	47,620	0.61	55,936	2,763	6,368	16,126	-7,019	2,744	4,361	11,566	-4,275	-2,658	4,547

Table 7: HRV simulation results for all house sizes and climate zones

CZ	House Size	Q [%]	Annual Energy [kWh]	ACH [/h]	TDV [$]	DALY LOW [$]	DALY MED [$]	DALY HIGH [$]	Δ(TDV) [$]	Δ(DALY) LOW [$]	Δ(DALY) MED [$]	Δ(DALY) HIGH [$]	TDV & DALY LOW [$]	TDV & DALY MED [$]	TDV & DALY HIGH [$]
3	111.5	100	12,443	0.48	14,352	3,367	6,363	16,267	0	0	0	0	0	0	0
3	111.5	50	13,264	0.43	15,178	3,689	7,059	18,121	-827	-322	-696	-1,854	-1,148	-1,523	-2,681
3	111.5	0	13,548	0.43	15,459	3,737	7,154	18,345	-1,107	-369	-791	-2,079	-1,476	-1,898	-3,186
3	195.1	100	20,918	0.39	24,016	3,857	7,415	19,050	0	0	0	0	0	0	0
3	195.1	50	22,038	0.35	25,165	4,246	8,241	21,240	-1,148	-389	-826	-2,189	-1,537	-1,975	-3,338
3	195.1	0	22,352	0.33	25,479	4,369	8,513	21,960	-1,463	-512	-1,099	-2,909	-1,975	-2,562	-4,373
3	250.8	100	26,733	0.41	31,167	4,643	8,888	22,803	0	0	0	0	0	0	0
3	250.8	50	27,896	0.37	32,366	5,069	9,795	25,206	-1,200	-426	-908	-2,403	-1,625	-2,107	-3,603
3	250.8	0	27,915	0.34	32,388	5,417	10,549	27,208	-1,221	-775	-1,662	-4,405	-1,995	-2,882	-5,625
12	111.5	100	11,937	0.50	20,275	3,245	6,120	15,603	0	0	0	0	0	0	0
12	111.5	50	12,592	0.45	20,902	3,571	6,808	17,432	-627	-326	-688	-1,829	-953	-1,315	-2,456
12	111.5	0	12,796	0.44	21,040	3,643	6,968	17,865	-764	-397	-848	-2,262	-1,162	-1,612	-3,027
12	195.1	100	19,525	0.41	32,431	3,687	7,051	18,109	0	0	0	0	0	0	0
12	195.1	50	20,451	0.37	33,342	4,061	7,846	20,208	-911	-374	-794	-2,100	-1,285	-1,705	-3,011
12	195.1	0	20,653	0.35	33,501	4,226	8,200	21,130	-1,070	-539	-1,149	-3,021	-1,610	-2,219	-4,091
12	250.8	100	24,720	0.43	41,539	4,441	8,463	21,664	0	0	0	0	0	0	0
12	250.8	50	25,728	0.39	42,610	4,836	9,314	23,902	-1,070	-395	-851	-2,238	-1,466	-1,921	-3,308
12	250.8	0	25,676	0.36	42,573	5,182	10,043	25,860	-1,034	-742	-1,580	-4,195	-1,776	-2,614	-5,229
16	111.5	100	17,941	0.50	22,469	3,297	6,226	15,906	0	0	0	0	0	0	0
16	111.5	50	19,085	0.45	23,536	3,597	6,854	17,577	-1,067	-300	-628	-1,672	-1,367	-1,695	-2,739
16	111.5	0	19,392	0.43	23,824	3,678	7,032	18,038	-1,355	-381	-806	-2,132	-1,736	-2,161	-3,487
16	195.1	100	30,193	0.41	37,387	3,780	7,246	18,620	0	0	0	0	0	0	0
16	195.1	50	31,801	0.36	38,923	4,133	8,001	20,641	-1,537	-354	-755	-2,022	-1,890	-2,291	-3,558
16	195.1	0	32,013	0.34	39,024	4,288	8,326	21,492	-1,638	-509	-1,080	-2,872	-2,146	-2,718	-4,510
16	250.8	100	40,115	0.43	49,096	4,507	8,598	22,058	0	0	0	0	0	0	0
16	250.8	50	41,902	0.39	50,890	4,904	9,443	24,294	-1,793	-397	-844	-2,236	-2,191	-2,638	-4,030
16	250.8	0	41,841	0.36	50,789	5,202	10,084	25,984	-1,693	-695	-1,486	-3,926	-2,387	-3,179	-5,619

Appendix B: REGCAP Building Energy Simulation Tool

REGCAP is capable of simulating minute-by-minute HVAC system operation as well as performing a heat and mass balance on the house and HVAC system. A key aspect of the tool is that it explicitly includes all the HVAC system related airflows including duct leakage and grille flows. The airflows include the effects of weather and leak location, and the interactions of HVAC system flows with house and attic envelope tightness. These interactions are particularly important because the airflows associated with ventilation systems (including duct leakage) significantly affect the pressure differences that drive natural infiltration in houses. REGCAP also includes models of air conditioner performance that include the effects of coil airflows and indoor and outdoor air temperature and humidity.

The tool has been validated in several previous studies. Average differences between measured and simulated ventilation rates are about 5% for a wide range of house leakage distributions and weather conditions (Wilson and Walker, 1992a, 1992b, Walker, 1993). The model validation used several years of hourly averaged tracer gas ventilation measurements in a climate that produced wind speeds up to 15 m/s, all wind directions, and indoor-outdoor temperature differences of up to 60°C. Predictions of combined mechanical and natural ventilation have less uncertainty (approximately 3%) because the fan airflow in or out of the building is well known. The ventilation and attic models were evaluated by Forest and Walker (1992), (1993a, 1993b), Walker (1993), and Walker et al. (2002). Average differences between measured and predicted attic ventilation rates were about 15%, and 10% for inter-zonal attic/house flows. The thermal distribution system interactions were evaluated by Siegel (1999), Walker et al. (1999), Siegel et al. (2000), Walker et al. (2001), and Walker et al. (2002). All of the verification shows a similar pattern. Specifically, the house and attic temperatures are predicted within 1°C. The duct supply and return temperatures are both predicted within 0.5°C when the air handler is on. When the air handler is off, REGCAP does not do as well at predicting duct temperatures, as it does not account for flows between different zones in the house or possible thermo siphon flows. The equipment model predicts energy consumption and capacity within 4% of measured capacity.

Appendix C: Simulation Details

C.1. Climate Zones

We used three California Climate zones: 3 (Oakland- coastal), 12 (Sacramento- hot), and 16 (Mount Shasta- cold). More specifically, we used Title 24 compliance TMY3 (NREL) hourly weather 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 (see Table 8).

Table 8: California Climate Zones 3, 12 and 16

Climate Zone	City	Latitude	Longitude	Elevation [m]
3	Oakland	37.7	122.2	6
12	Sacramento	38.5	121.5	17
16	Mount Shasta	39.3	120.7	1609

(Latitude and altitude taken from ACM joint Appendix)

C.2. Prototype Houses

We modeled three houses based on the T24 prototypes:

- Small (1 story, 3 bed, 2 bath): 111 m^2 [1,200 ft^2] Custom, based on T24 Prototype C
- Medium (1 story, 3 bed 3 bath): 195 m^2 [2,100 ft^2] T24 Prototype C
- Large (2 story, 4 bed, 3 bath): 251 m^2 [2,700 ft^2] T24 Prototype D

Figure 6and Figure 7, respectively, show the geometry of the medium and large houses, based on information listed in the 2008 Title 24 Residential Standards (CEC, 2008a). The smaller house was a scaled down version of the medium sized house. All had uniform 2.5 m ceilings. The garages were omitted from the simulations and treated as outside.

Window area was 20% of floor area and evenly distributed between the four walls. Appropriate insulation R-values were also taken from Title 24.

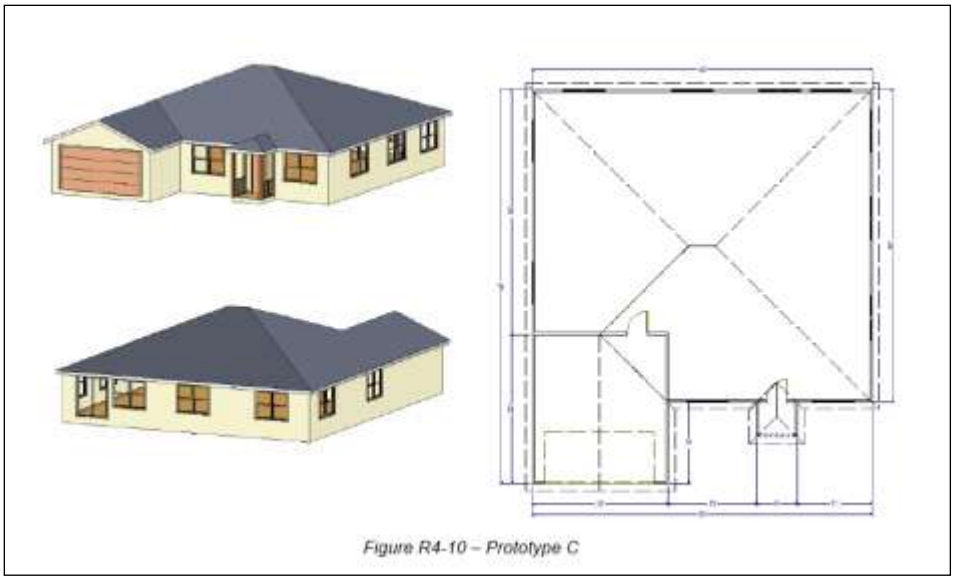

Figure 6 - Title 24 Housing Prototype C

Figure 7 - Title 24 Housing Prototype D

C.3. Building Sensible and Latent Loads

Building loads were derived from T24 and ASHRAE Standards (Table 9). The daily sensible gain from lights, appliances, people and other sources used the ACM value of 20,000 Btu/day for each dwelling unit plus 15 Btu/day for each square foot of conditioned

floor area (CEC, 2008a). Loads were delivered to the occupied zone at a constant rate throughout the day. We did not use seasonal adjustments.

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

Table 9: Internals loads for the prototype houses based on T24 (sensible) and ASHRAE Draft Standard 160P (moisture generation)

House	Number of Occupants	Sensible Load [W]	Moisture Generation [kg/day]
Small (1,200 ft^2)	4	464	277 [9.8]
Medium (2,100 ft^2)	4	629	277 [9.8]
Large (2,700 ft^2)	5	739	291 [10.3]

C.4. Heating and Air Conditioning System

Each house was equipped with a gas-fired space heating system and a direct-expansion compressor-based cooling system. The heating system used an 80% AFUE natural gas furnace. The cooling system used a SEER 13 EER 11 split-system air conditioner with a TXV refrigerant flow control, and we assumed that the system had correct refrigerant charge and airflow. Heating and cooling equipment sizing used average values for climate zone 12 from Chitwood's unpublished field surveys of California homes (Table 10). Climate zones 3 and 16 assumed similar equipment oversizing as zones that were included in the field study. Operation of the heating and cooling equipment used time-of-day dependent thermostat settings (Table 10).

Table 10: HVAC Equipment Sizing

Climate Zone and Location	Source	Cooling Sizing		Heating Sizing	
		[kW/100m^2]	[tons/1000 ft^2]	[kW/100m^2]	[(kBtu/h)/1000 ft^2]
CZ 03 – Oakland	Manual J with similar oversizing	3.5	1.0	10.5	35.9
CZ 12 - Sacramento	Chitwood Field Survey	5.6	1.6	11.9	40.5
CZ 16 – Mount Shasta	Manual J with similar oversizing	3.9	1.1	14.5	49.6

Table 11: Thermostat Settings for Ventilation Simulations (°F)

Hour	Cooling Sizing		Heating Sizing	
	[C°]	[°F]	[°C]	[°F]
00:00 to 07:00	20.0	68	25.0	77
07:00 to 16:00	21.1	70	26.7	80
16:00 to 00:00	21.1	70	25.0	77

Duct leakage to outside was 6%, split between 3% supply leakage and 3% return leakage. Duct area followed the ACM Title 24 standard design of 27% for the conditioned floor area for the supply and 5% for return (1 story), or 10% (2 stories).

C.5. Building Occupancy and Source Control Ventilation

We assumed that occupants were absent from 8 a.m. to 4 p.m. weekdays and present at all times over weekends.

There was one shower per occupant per day with the bathroom fan operating continuously for 30 minutes (see Table 12). At weekends there was still 30 minutes of fan operation per occupant per day but these were randomly distributed between the hours of 7a.m. and 7p.m. to reflect the less uniform weekend routines of occupants (these randomly generated schedules were kept constant across the different simulations).

Table 12: Bathroom Fan Operation Schedule for Weekdays

House Size	Bathroom		
	1	2	3
Small (1,200 sq. ft.)	06.30 to 07.30	06.30 to 07.30	-
Medium (2,100 sq. ft.)	06.30 to 07.30	07.00 to 07.30	07.00 to 07.30
Large (2,700 sq. ft.)	06.30 to 07.30	06.30 to 07.30	07.00 to 07.30

For each occupant there was an additional 10 minutes of bathroom fan operation per day to account for use of the W.C. Monday to Friday these occurred randomly between the hours of 4 p.m. and 11 p.m. Weekends between 7 a.m. and 11 p.m. Intermittent bathroom fans had the 25 L/s (50 cfm) per bathroom specified in 62.2. The Panasonic FV-08VKM2 is a 25 L/s fan rated at 10.2 W and <0.3 sone.

All simulations had kitchen fan operation. Based on input from ASHRAE Standard 62.2 members and an ARTI project monitoring committee, kitchen fans operated for one hour per day from 5.30 p.m. to 6.30 p.m. There was an additional 30 minutes of operation between 9.30 a.m. and 10 a.m. at weekends. Kitchen fans were sized to meet the 62.2 requirements for intermittent kitchen fans of 50 L/s (100 cfm). The Venmar C27030BL is a 50 L/s fan rated at 37.2 W and 0.8 sone.

The schedule for the dryer fan assumed two days of laundry each week for the small and medium sized houses (Sunday and Wednesday) and three days for the larger house (Sunday, Wednesday and Friday). The dryer operated continuously for three hours per laundry day between 11 a.m. and 2 p.m. irrespective of occupancy (as if on a timer). Clothes dryer fans were 75 L/s (150 cfm) exhaust fans. All fans were chosen from the 2011 HVI Directory.

C.6. Ventilation

Whole-house exhaust ventilation rates are displayed in Table 13 and HRV details are contained in Table 14.

Table 13: Whole-house exhaust airflow rates as a percentage of the minimum 62.2 whole-house ventilation rate.

House	25%		50%		75%		100% (62.2)		200%		300%	
	[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]
Small (1,200 ft^2)	4.9	10.5	9.8	21.0	14.7	31.5	19.6	42.0	39.2	84.0	58.8	126.0
Medium (2,100 ft^2)	6.0	12.7	11.9	25.5	17.9	38.2	23.8	51.0	47.6	102.0	71.4	153.0
Large (2,700 ft^2)	7.6	16.2	15.2	32.5	22.8	48.7	30.4	64.5	60.8	130.0	91.2	195.0

Table 14: HRV systems used in the simulations for the three different house sizes

House	HRV System	Airflow Rate		ASE*	Power
		[L/s]	[cfm]	[%]	[W]
Small (1,200 ft^2)	VENMAR- AVS Constrcto 1.5V	40	80	75	64
Medium (2,100 ft^2)	GREENTEK- DH 7.15	56	112	75	114
Large (2,700 ft^2)	BROAN-NUTONE- Maytag	65	130	72	124

*ASE = Apparent Sensible Effectiveness