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Assessment of Indoor Air Quality Benefits and Energy Costs of Mechanical Ventilation

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Abstract and Implications

Intake of chemical air pollutants in residences represents an important and substantial health hazard. Sealing homes to reduce air infiltration can save space conditioning energy, but can also increase indoor pollutant concentrations. Mechanical ventilation ensures a minimum amount of outdoor airflow that helps reduce concentrations of indoor emitted pollutants while requiring some energy for fan(s) and thermal conditioning of the added airflow. This work demonstrates a physics based, data driven modeling framework for comparing the costs and benefits of whole-house mechanical ventilation and applied the framework to new California homes. The results indicate that, on a population basis, the health benefits from reduced exposure to indoor pollutants in New California homes are worth the energy costs of adding mechanical ventilation as specified by ASHRAE Standard 62.2.

This study determines the health burden for a subset of pollutants in indoor air and the costs and benefits of ASHRAE's mechanical ventilation standard (62.2) for new California homes. Results indicate that, on a population basis, the health benefits of new home mechanical ventilation justify the energy costs.

Citation

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Introduction

Exposure to pollutants in indoor air can have a substantial effect on human health. The increased emphasis on reducing residential energy demand has led to the construction of tighter homes and the air sealing of existing homes. Tightening or air sealing of homes to reduce outdoor air infiltration and improve energy efficiency can lead to higher indoor air pollutant concentrations and health risks in the absence of accompanying mitigation measures (Sherman et al. 2011).

Mechanical ventilation ensures a minimum amount of outdoor airflow that helps reduce concentrations of indoor emitted pollutants while requiring some energy for fan(s) and thermal conditioning of the added airflow. The American Society of Heating, Refrigerating and Air Conditioning Engineer's (ASHRAE's) Standard 62.2 is the most widely accepted residential ventilation standard in the United States. ASHRAE 62.2 includes provisions for both local and overall ventilation. The overall ventilation rate – specified as a continuous or equivalent intermittent mechanical ventilation rate – is a function of home size and number of bedrooms. The size of the house is a surrogate for pollutants from materials intrinsic to the building, and the number of bedrooms is a surrogate for home-occupancy dependent activities and associated emissions. Given the energy demands of mechanical ventilation, there is interest in determining if the costs are worth the health benefits.

This paper describes a modeling study that estimates baseline health impacts associated with air tightening of new homes and explores the energy costs and health benefits of whole-house mechanical ventilation. The modeling work addressed homes in three conditions: 1) infiltration only, the homes have no mechanical ventilation; 2) unbalanced whole house mechanical ventilation in addition to infiltration; and 3) balanced whole house mechanical ventilation in addition to infiltration. This work focuses on the new California housing stock, but the methodology can be applied to other housing cohorts.

Methods

This work used two distinct modeling frameworks: an indoor pollutant mass balance model and a residential energy use model. Both models used distributions of measured and surveyed new home data as inputs. The main input data sources used in this study were the California New Home Study (CNHS) (Offermann 2009) and the 2003 Residential Appliance Saturation Survey (RASS) (KEMA-XENERGY 2004). Outdoor concentrations were set to the values modeled by the EPA's 2002 National Air Toxics Assessment (EPA 2009). This modeling work focused on 14 common VOCs in the indoor environment that have been identified as presenting a potential health problem through the inhalation exposure pathway: 1,4-dichlorobenzene, acetaldehyde, benzene, chloroform, d-limonene, formaldehyde, hexane, naphthalene, styrene, tetrachloroethene, toluene, vinyl acetate, m,p-xylene, and o-xylene.

The mass balance model calculates hourly indoor pollutant concentrations based on whole house emission rates, volume, and time-dependent outdoor air exchange over the course of a year. The governing equation for the mass balance model is:

$$\frac{dC}{dt} = \frac{S}{V_{house}} - AC - kC + pAC_{out} \quad (1)$$

In this equation, V_{house} is volume of the residence (m^3), C is the indoor concentration ($\mu g\ m^{-3}$), S is the emission rate ($\mu g\ h^{-1}$), C_{out} is the outdoor concentration ($\mu g\ m^{-3}$), A is the air exchange rate (1/hr), k is the first order loss rate, and p is the penetration coefficient. For this version of the model we are exploring only VOCs, therefore the first order loss rate is treated as negligible and the penetration coefficient is set to 1.

We used a simple time-step modeling approach to calculate indoor concentrations as a function of mechanical and natural ventilation. The discretized form of equation 1 for pollutant *j* at time step *i* is:

$$C_{j,i} = C_{j,i-1}\exp(-A_i\Delta t) + \frac{\left(\frac{S_j}{V_{house}} + A_i C_{j,out}\right)(1 - \exp(-A_i\Delta t))}{A_i} \qquad (2)$$

A time step, ΔT, of 1 hour was found to be small enough to keep the Equation 2 calculations stable. For each run, initially $C_{i=0}$ 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 the model to reach dynamic equilibrium and to eliminate the effect of the initial conditions on the solution.

The total air exchange rate, A_i, varies diurnally and seasonally. Both infiltration and mechanical ventilation contribute to the total air exchange rate. We determined the hourly whole house infiltration as a function of outdoor wind speed, indoor-outdoor temperature difference, and home normalized leakage using the approach outlined by Sherman (2008). Mechanical ventilation, when included, was combined with infiltration additively if the mechanical ventilation system was balanced and by quadrature if the system was unbalanced. Unbalanced whole house mechanical ventilation was assumed to be supplied by a whole house exhaust fan sized to exactly meet the requirements for ASHRAE standard 62.2. For the balanced ventilation scenario, it was assumed that a heat recovery ventilator (HRV) was used and that the HRV was connected to the home’s central heating and cooling system.

The mass balance model was applied through Monte Carlo sampling to simulate one year of operation for homes distributed throughout California. The model samples input parameters from measurements and survey data from new and existing homes. Emission rates and leakage areas were taken from CNHS. New home locations, volumes, and number of bedrooms from RASS. Outdoor concentrations from NATA. The output of the mass balance model, distributions (across homes) of calculated pollutant concentrations, are combined with assumptions about occupancy patterns and inhalation rates to estimate population intake, then health impact factors from the literature are used to quantify total harm attributable to indoor air pollution.

We used the approach of Disability Adjusted Life Years (DALYs) to calculate health impacts as a function of exposure. DALYs are a measure of overall disease burden and incorporate both disease likelihood and severity. DALYs are reported as the equivalent number of years lost from premature death and disability and offer a way to compare mortality and morbidity. In order to determine the total health burden from breathing indoor air, we assumed two adults and two children in each home. We used the method outlined by Huijbregts et al. (2005) to determine the annual health burden per 100,000 homes based on estimated annual exposure.

For this work, the home energy modeling was performed using the REGCAP model (Walker and Sherman 2006). The model calculated energy for thermal conditioning and fan use, accounting for thermal loads (people, sun, etc.) and specifically changes in airflow on a minute-by-minute basis for one year. The model was run for 80 homes that were thought to represent the new California housing stock. The weighted results of the energy modeling yielded a distribution (across homes) of annual average home energy use for ventilation and thermal conditioning. These values were used to determine increased cost of adding mechanical ventilation to new California homes.

Results

Figure 1 shows the distribution of whole house air exchange rates for the three scenarios. Unbalanced mechanical ventilation increases average AER by about 0.2 1/h and balanced ventilation increases AER by about 0.4 1/h. Figure 2 shows the distribution of indoor concentrations for formaldehyde, a pollutant with significant indoor sources in most homes, and 1,4-dichlorobenzene, a pollutant with significant indoor sources in very few homes. The effectiveness of ventilation depended heavily on the pollutant source properties.

Table 1 shows the calculated total annual energy use and annual DALYs lost per year per 100,000 new California homes (assuming an occupancy of 4 people per home) using the methodology described above. The health impacts are per year of living in a new home. Adding unbalanced ventilation results in an estimated 41% reduction in annual DALYs lost but an increase in ventilation and space conditioning energy use of 14%. Adding balanced ventilation results in an estimated 54% reduction of DALYs lost and an increase in HVAC energy use of 21% per year. The estimates of total DALY impacts are based on the central estimates for damage-per-intake, and are thus subject to uncertainty of about a factor of 25, in the sense that multiplying or dividing by 25 is believed to encompass 95% of the probability. The high end of this range is excessive based on estimates of overall DALYs lost per year in the US (WHO 2009), however reducing this uncertainty will be difficult because the main sources of uncertainty are the extrapolations of toxicological studies of health impacts across species and exposure durations. Fortunately, as long as damage-per-intake is fairly linear over the range of residential exposures, the ratio of ΔDALYs/ DALYs$_{base\text{-}case}$ is unaffected due to cancellation in the numerator and denominator. Unfortunately, a relevant factor in a decision analysis or cost-benefit analysis is DALYs saved per actual (not relative) energy expended or cost, in the case of ventilation improvements – that is, ΔDALYs /ΔEnergy or ΔDALYs /Δ\$US – and this is very uncertain.

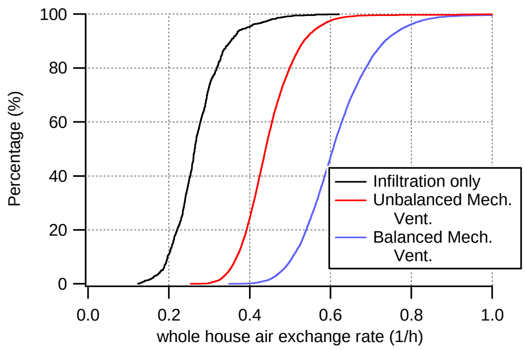

Figure 1. Distributions of whole house air exchange rate for homes with and without mechanical ventilation.

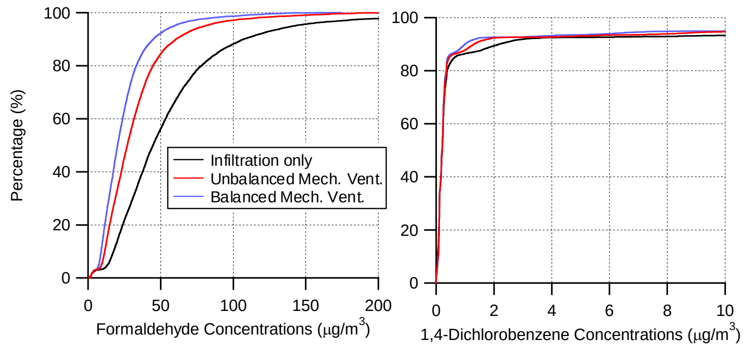

Figure 2. Distributions of indoor concentrations for formaldehyde and 1,4-dichlorobenzene for homes with and without mechanical ventilation.

Table 1. Energy use (E) in 10^{-3} quads and DALYs (D) per 100,000 households per year

Ventilation Cases	*Energy (quads /10^{-3})*	*ΔE ($\Delta E/E_{base-case}$)*	*DALYs lost (years)*	*ΔD ($\Delta D/D_{base-case}$)*
Base Case-Infiltration only	3.5	-----	160	-----
Unbalanced Mechanical Ventilation	4.0	5 (14%)	90	70 (-41%)
Balanced Mechanical Ventilation	4.3	8 (21%)	70	90 (-54%)

Discussion

Pollutants Not Included in this Analysis

The limited nature of this work means that some very important pollutants were left out of the analysis, most importantly acrolein, NO_2, and $PM_{2.5}$. Offermann (2009) found that for his sample of 108 California homes, the geometric mean concentration measured indoors was roughly 50-100% higher than the outdoor concentration for both $PM_{2.5}$ (indoor: 11µg/m^3; outdoor: 7.5 µg/m^3) and NO_2 (indoor: 6.2 µg/m^3; outdoor: 3.4 µg/m^3). Reducing indoor concentrations of these pollutants to outdoor levels could lead to a central mean estimate of 1% reduction in annual mortality (40 prevented deaths per year per 100,000 new California homes (400,000 people)) and 2800 fewer cases of respiratory illness annually in new homes in California. Based on our calculations of disease incidence using relevant disease incidence models (EPA 1999; Huijbregts et al. 2005) and published disease damage factors (Hall et al. 2010), the central estimate of savings due to reducing indoor concentrations of NO_2 and $PM_{2.5}$ to outdoor levels is 800 DALYs per 100,000 California new homes. A review of indoor residential concentrations found that acrolein concentrations were on the order of 3-4 µg/m^3 indoors (Logue et al. 2011). This results in a central estimate of the average health burden on the order of 300 DALYs per year per 100,000 households.

Accurately modeling the effects of intermittent indoor sources and mitigation techniques on indoor concentrations and health effects of $PM_{2.5}$, NO_2, and acrolein requires a substantially more complicated model and additional data. As these pollutants appear to be much larger risk drivers than those included in this initial analysis, the effort seems warranted.

Comparing the Costs and Benefits of Mechanical Ventilation

The REGCAP model was run for gas heated homes equipped with HVAC equipment that complies with the energy efficiency sections of California's building code (Title 24). According to the U.S. Energy Information Administration, the average cost of electrical energy per kilowatt-hour (kWh) is $0.152, the average cost per thousand cubic feet of natural gas is $12.75 ($0.044/kWh). This yields an average cost per DALY avoided of $150,000 for the 14 pollutants included in the modeling for unbalanced mechanical ventilation compared to infiltration only. The average cost of adding balanced ventilation to a home is $240,000 per DALY avoided compared to infiltration only.

Projected values for DALYs are on the order of $50,000 - $160,000 (Lvovsky et al. 2000; Brown 2008). Since the 14 pollutants studied here appear to be less than a third of the DALYs due to indoor exposure (with most of the remainder attributed to $PM_{2.5}$, NO_2 and acrolein), the results indicate that the energy cost of mechanical ventilation is on par with the expected benefits for gas heated homes.

This analysis only compared annual energy expenditures and health benefits for gas heated homes. For homes with electric heating, given the higher cost per KWh for electricity, a balanced system may make more sense than an unbalanced system in terms of energy use because the heat recovery ventilator reduces the energy burden of heating the added air flow. More analysis is needed to determine if this is the case. Additionally, more work needs to be done to determine if the initial capital and labor cost of adding exhaust to a new or existing home is worth the benefits.

CONCLUSIONS

Despite its limited scope, some interesting conclusions can be drawn from the analysis presented here. Considering the best available estimate of the health burden associated with specific pollutants, the comparison of the costs and benefits of residential ventilation appear to suggest that, as long as you are not bringing in harmful amounts of outdoor pollutants, the energy cost of adding mechanical ventilation is worth the health benefits. The methods developed here are broadly applicable to the analysis of pollutants of concern indoors. The next step in this analysis will be to incorporate $PM_{2.5}$, acrolein, and NO_2 to the model and to expand the model to cover a larger subset of home conditions.

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Supplemental: Health Effects Included in Study

Determining Health Damage as a Function of Concentration

Assigning damage to specific levels of chronic intake exposure in this work relied heavily on the work of Huijbregts et al. (2005). Huijbregts et al. (2005) computed expected ranges of human damage and effect factors for the non-cancer and cancer chronic effects of 1,192 substances, applying equal weightings for a year lost, independent of age (i.e. zero discounting). Using the values determined by Huijbregts et al. (2005), the DALYs lost for one year of breathing pollutant *i* was calculated using the following equations:

$$DALYs_i = \frac{\partial Damage}{\partial Intake}_i * intake_i \quad \text{(S.1)}$$

$$DALYs_i = C_i * V * \left(\frac{\partial D_{cancer}}{\partial Intake_i} * ADAF + \frac{\partial D_{non-cancer}}{\partial Intake}_i \right) \quad \text{(S.2)}$$

where $\frac{\partial D_j}{\partial Intake_i}$ are the cancer and non-cancer mass intake-based damage factors, C_i is the indoor concentration, and V is volume of air breathed in the residence each year. This formulation assumes that the damage-intake relationship is linear in the range of interest: from intake due to outdoor exposure only, to intake that includes both indoor and outdoor exposure. A nonlinear relationship below (or above) this range will not affect our DALY estimates.

Huijbregts et al. (2005) presented, for each chemical, both a central estimate and the estimated uncertainty of the damage per mass-intake of pollutant; uncertainty was assumed to be log-normal, characterized by a factor, *k*, equal to:

$$k = \sqrt{\frac{97.5th\ percentile}{2.5th\ percentile}} \quad \text{(S.3)}$$

which includes the aggregated uncertainty of the rate of disease incidence as well as the uncertainty in the damage per incidence of disease. In this study we assumed that the central estimates were the best estimate of actual damage and costs were calculated based on the sum of the central estimate of damage for each pollutant

Intake-Based Damage Factors

Huijbregts et al. (2005) determined cancer and non-cancer mass intake-based damage factors, $\frac{\partial D_j}{\partial intake_i}$, by synthesising disease damage factors and animal toxicology based disease incidence rates.

$$\frac{\partial D_j}{\partial Intake_i} = \frac{\partial Damage}{\partial Disease\ incidence} * \frac{\partial Disease\ incidence}{\partial intake} \quad \text{(S.4)}$$

Disease damage factors were taken from the quintessential work of Murray and Lopez (1996b; 1996a). Murray and Lopez determined the damage associated with each disease incidence based on years of life lost and the perceived loss of quality of life for the years of illness included in the disease (1996b; 1996a). For each incidence of disease a specific level of DALYs lost was assigned.

Disease incidence factors were determined based on ED50 (intake level at which 50% of the population is effected) values taken from the animal toxicity literature. The ED50 for carcinogenic effects were taken from the Carcinogenic Potency Database developed by Gold and Zeiger. ED50s for non-carcinogenic effects were extrapolated from dose-response data reported in the EPA Integrated Risk Information System. For both cases, if there was more than 1 available study, Huijbregts et al. (2005) selected data based on a set species preference of (from best to worst choice) monkey, dog, rat, hamster, and mouse.

The CPDB indicates the animal that was used to determine carcinicity, ED50, and the site of the effect in the animal. Huijbregts et al. (2005) derived human disease incidence rates from the animal disease incidence rate and identified the human cancer associated with those effects to determine the damage associated with the incidence of cancer. If no single appropriate human endpoint cancer could be determined for a specific chemical, than a prevalence averaged cancer damage value was used. Table S.1 summarizes this data for the chemicals included in the analysis in this paper.

For non-cancer effects, Huijbregts et al. (2005) determined the ED50 from no effect, low effect, and benchmark dose (BMD) animal toxicity data. From these values, they extrapolated the disease incidence rate. Huijbregts et al. (2005) aggregated damages associated with 32 non-cancer disease endpoints representative of the world in 1990 and determined the prevalence based average damage from a non-cancer endpoint. If a non-cancer effect was observed, the damage per incidence of disease was set to this average non-cancer damage value.

Table S.1 Cancer and non-cancer impacts for chemicals included in health cost study.

	CANCER HEALTH IMPACTS			NON-CANCER IMPACTS
Chemical	**Animal**	**Animal Effect Site**	**Human Cancer Used to Access Damage (DALYs)**	**Health Effect?**
acetaldehyde	hamster	nasal, oral	Trachea, bronchus and lung cancer	X
benzene	rat	esophagus, nasal, oral cavity, skin, stomach, vascular system	Trachea, bronchus and lung cancer	X
chloroform	rat	kidney, liver	Liver cancer	
d-limonene	rat	kidney	Prevalence based average of main cancers	
dichlorobenzene, 1,4-	rat	kidney	Prevalence based average of main cancer damages	X
formaldehyde	rat	nasal, hematopoietic system	Leukemia	X
hexane	---	not applicable	Not applicable	X
naphthalene	rat	nasal	Trachea, bronchus and lung cancer	X
styrene	rat	mammary gland	Breast Cancer	X
tetrachloroethene	rat	Kidney, hematopoietic system	Leukemia	
toluene	rat	oral cavity	Mouth and oropharynx cancer	X
vinyl acetate	rat	liver, nasal, thyroid, uterus	Liver cancer	X
xylene, m,p-	rat	oral cavity	Mouth and oropharynx cancer	x
xylene, o-	rat	oral cavity	Mouth and oropharynx cancer	x