Evaluating Indoor Air Quality and Energy Impacts of Ventilation in a Net-Zero Energy House Using a Coupled Model

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The National Institute of Standards and Technology constructed the Net-Zero Energy (NZE) Residential Test Facility to support the development and adoption of cost-effective NZE designs and technologies. In support of indoor air quality goals, contaminant source control approaches were implemented that minimized the use of products containing urea-formaldehyde resin and utilized products with relatively low volatile organic compound emissions. Indoor and outdoor concentrations of formaldehyde and acetaldehyde were measured approximately monthly for 15 months. Independent emission measurements of formaldehyde were made in a small chamber system to determine the emission rates from samples of the wood flooring, plywood, and wood cabinetry taken from the house. Blower door tests were performed to determine the leakage area of the exterior envelope, the interior floors, and transfer grilles between floors. Real-time formaldehyde concentration and energy measurements were used to verify the indoor concentrations and energy predictions of a coupled CONTAM-EnergyPlus model of the house. The verified model was then used to evaluate the impacts of different outdoor air ventilation rates on indoor concentrations and energy. This work demonstrates the need for consideration of source control options during product selection and the provision of mechanical ventilation, especially in homes with relatively airtight envelopes.

Introduction

Buildings consumed 41 % of all energy used in the United States in 2011, with residential buildings accounting for 22 % (DOE 2011). In addition to consuming more energy than the transportation or industrial sectors, buildings represent the fastest growing sector of energy usage (DOE 2011). In response, goals for achieving net-zero energy (NZE) performance have been established in the United States and around the world (CEC 2015; EPBD 2010; IEA 2014). A NZE building is an energy-efficient building where the actual annual delivered energy is less than or equal to the on-site renewable exported energy (DOE 2015a).

The pursuit of NZE buildings is often undertaken with little or no verification of the achievement of acceptable indoor air quality (IAQ). Teichman et al. (2015) reviewed 100 cases of high performance buildings and found that 60 implemented source control by using low-VOC (volatile organic compounds) emitting materials but generally provided little information on the specifics supporting these claims. Only two of the case studies measured actual airborne chemical concentrations in the building. Concentration verification is a vital step in buildings with low air change rates, as low-VOC emitting building materials can still result in elevated concentrations if building ventilation rates are not adequate or if chemicals are emitted that are not accounted for in the emissions testing.

Two contaminants of concern in the indoor environment are formaldehyde and acetaldehyde. According to the International Agency for Research on Cancer (IARC), formaldehyde is a human carcinogen (IARC 2006) and acetaldehyde is a probable human carcinogen (IARC 1999). The U. S. Environmental Protection Agency (EPA) does not define any acceptable exposure levels to carcinogens but does define unit risk factors to estimate inhalation cancer risk from chronic exposure to a chemical. A user can define the acceptable risk level and use the unit risk factor to determine the airborne chemical concentration equivalent to that acceptable risk level. In this study, risk levels of 1 cancer in 1 000 000 people (10^{-6}) and 1 cancer in 10 000 people (10^{-4}) from exposure to formaldehyde and acetaldehyde were evaluated, which are lower and upper risk levels that have been used by the EPA for air toxics in outdoor air (EPA 1999).

In addition to cancer effects, both formaldehyde and acetaldehyde can have chronic harmful (i.e., deleterious) noncancerous impacts, including eye, nose or throat irritation. California (OEHHA) chronic relative exposure level (cREL) (OEHHA 2016) and the EPA inhalation reference concentration (RfC) are both concentrations below which there are deemed to be no harmful noncancerous impacts (EPA 1988; EPA 1989). These health impact levels, although not specific to indoor air, can be used to put measured and modeled indoor formaldehyde and acetaldehyde concentrations into perspective. The levels of formaldehyde and acetaldehyde associated with the cancer risks and harmful noncancerous impacts are listed in Table 1. For comparison, the permissible exposure limit (PEL) for formaldehyde is over 900 μg m^{-3} issued by the U. S. Occupational Safety and Health Administration (OSHA 2010), which is 100 times higher than the cREL.

In this study, energy and IAQ measurements were made in a net-zero test house. The measurements were then used to verify the performance of a coupled thermal-airflow model of the house. The coupled model was then used to simulate the energy use and indoor concentrations of formaldehyde and acetaldehyde for different outdoor air ventilation rates. This paper presents details of the test house, the measurements conducted as part of this study and the coupled simulation model, as well as a discussion of the results.

Test House

The Net-Zero Energy Residential Test Facility (NZERTF) was constructed at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland to support the development and adoption of cost-effective NZE designs, technologies, and construction methods. The two-story house shown in Figure 1 has a basement and attic, and is similar in size and aesthetics to homes in the surrounding communities. The occupiable floor area consists of the first and second floor (1F and 2F) and is 242 m^2. The total floor area of the house (basement, 1F and 2F, attic) is 485 m^2. The house is unoccupied and not furnished other than permanently installed cabinetry. Despite it being unoccupied, the activity of a family of four was simulated in terms of electrical use (appliances and lighting), hot water use, and metabolic heat and moisture generation.

Many technologies were utilized to achieve the NZE goals including a 10.2 kW photovoltaic (PV) system, a high efficiency central air-to-air heat pump, a solar hot water system, and a heat recovery ventilator (HRV). The central heat pump system provides supply air to all floors except the attic. The cooling setpoint was 24 °C and the heating setpoint was 21 °C with no setback. Passive air transfer grilles connect the basement to the first floor and the attic to the second floor of the house. Air is returned to the heat pump via three return air grilles located on the first and second floors. A balanced, ducted HRV system supplies outdoor air to the first floor living area and second floor bedrooms and draws return air for heat recovery from one bathroom located on the first floor and two on the second floor. To comply with the minimum ventilation requirements of ASHRAE Standard 62.2-2010 (ASHRAE 2010), the HRV was sized to deliver 137 m^3 h^{-1} of outdoor air (0.09 h^{-1} based on the volume of the basement, 1F, 2F, and attic). However, the installed HRV delivered 171 m^3 h^{-1} (0.11 h^{-1}). The ventilation rate based on Standard 62.2-2010 was not adjusted to include any infiltration credit. More information on the NZERTF design can be found in Pettit et al. (2014).

The NZERTF was built to minimize use of products containing urea-formaldehyde resin and with preferences for products that had low emissions of VOCs. The approaches used for the building product selection and construction best practices for IAQ at the NZERTF are available as architectural specifications in Bernheim et al. (2014). After construction of the home, indoor and outdoor concentrations of formaldehyde and 30 other VOCs were measured approximately monthly during the first 15 months of house operation, and the results are reported in Poppendieck et al. (2015). Formaldehyde emission factors in the unoccupied NZERTF are on average at least four times lower than homes from other recent studies. However, the NZERTF concentrations of some VOCs were higher than in those same homes, which had average air change rates that were 20 % higher than those of the NZERTF (Ullah et al. 2016).

Measurements

This section presents the measurements made of contaminants, airflow, energy and indoor environment related parameters. Contaminant concentrations were measured for acetaldehyde and formaldehyde. Together with airflow measurements, these concentration measurements enabled the determination of average, whole-house emission rates of both acetaldehyde and formaldehyde. Airflow-related measurements included building envelope and interzone leakage areas, whole-house outdoor air change rates, and ventilation system airflow rates. Energy-related measurements included power consumption of appliances, lighting, and heating, ventilating, and air-conditioning (HVAC) equipment. Indoor environmental measurements included dry bulb temperature and relative humidity. The contaminant emission rates, indoor temperature and relative humidity, and airflow-related measurements were used as inputs to the coupled building model. The contaminant concentration and energy measurements were used to verify the model.

Acetaldehyde measurements in the NZERTF were made approximately monthly for 15 months between May 2013 and July 2014. One hour samples were taken at a 1.0 L min^{-1} sampling rate and collected onto 2,4-dinitrophenylhydrazine (DNPH) cartridges according to ASTM D5197 (ASTM 2009). The average effective acetaldehyde emission rate was determined to be 7.4 μg h^{-1} m^{-2}, which was normalized over the floor area of all four floors and accounted for sources, sinks and reactions within the NZERTF (Poppendieck et al. 2015). The measured outdoor acetaldehyde and formaldehyde concentrations were both on average 0.8 μg m^{-3} based on periodic measurements during the 15-month span (Poppendieck et al. 2015). It should be noted that these measured outdoor concentrations are both above the level associated with a cancer risk of 1 in 1 000 000 (0.5 μg m^{-3} for acetaldehyde and 0.08 μg m^{-3} for acetaldehyde).

The emission of volatile organic chemicals from building materials has been characterized by two laboratory approaches: (1) a mass transfer approach, and (2) an empirical approach (Xiong et al. 2016). The mass transfer approach characterizes the diffusion of the chemical through the material (internal mass transfer processes described by the diffusion coefficient), the partition of the chemical from the material surface to the air phase (described by the partition coefficient) and the migration of the chemical through the air boundary layer on the material surfaces (external mass transfer processes described by the convective mass transfer coefficient). The mass transfer approach allows for the impact of varying environmental conditions (for instance air flow differences between a chamber study and an actual room) on emission rates to be modeled. However, the mass transfer approach requires complex experiments (separate experiments are required to determine the initial chemical concentration and to determine the diffusion and partition coefficient) and modeling (Zhang et al. 2007). In addition, when using the mass transfer approach, the convective mass transfer coefficient in the modeled environment must be assumed. The empirical approach for the emission chemicals from building materials ignores the potential influence of the external mass transfer processes. This may result in the emissions being different in actual rooms compared to a chamber environment. Nevertheless, an empirical modeling approach was utilized for this effort because 1) the uncertainties in building model parameters (e.g. the interzonal airflow rates) may be greater than uncertainties in the emission model; 2) the materials in this study were over five years old when tested likely resulting in an internally mass transport limited emission that would not be impacted by varying flow rates and 3) the materials did not contain urea-formaldehyde. Most of the existing formaldehyde mass transfer emission modeling has been performed using urea-formaldehyde based materials.

The formaldehyde emission rate was determined from small samples that were removed from the NZERTF including: wood flooring (0.033 m^2), cabinet (0.106 m^2) and two plywood samples (0.077 m^2 and 0.070 m^2). The wood flooring was cut from an access panel in the NZERTF. The cabinet was from a small shelf in the kitchen. The wood flooring and plywood were removed from the NZERTF in the summer of 2016 and tested in spring 2017. The cabinet was removed immediately prior to testing in spring 2017.

The back and edges of each sample were covered with aluminum foil and sealed with foil tape. The samples were placed in a 51 L, stainless steel emission testing chamber. Chamber air temperature, relative humidity, airflow rate and formaldehyde concentration were all measured and recorded over at least one minute intervals. The airflow rate was held constant at an air change rate of 0.93 h^{-1} (95 % confidence interval: 0.926 h^{-1} to 0.929 h^{-1}) and the relative humidity at 52 % (95 % confidence interval: 51.5 % to 52.9 %). The temperature was increased by roughly 2.0 °C increments from 17 °C to 31 °C, to reflect the location from which the material was removed from the NZERTF, i.e., attic or basement. The temperature was held constant after each incremental change for at least 24 h, hence the material was assumed to be the same temperature as the recorded air temperature. A total of 28 experiments were performed (5 cabinet, 7 flooring, and 16 plywood). Experiments were run at least until the chamber formaldehyde concentration reached steady state (approximately 6 h). Equilibrium concentrations were then used to calculate the area-specific emission rate (E_{AS}) for the materials at the measured temperature using Equation 1. Chamber inlet concentrations of formaldehyde were about 0.2 µg m^{-3}.

$$\boldsymbol{E_{AS}} = \frac{Q(C_{SS}-C_{in})}{A} \qquad \text{(}\textbf{Error! Bookmark not defined.}\text{1)}$$

where:

Q	airflow into the chamber (m^3 h^{-1})
C_{SS}	steady state formaldehyde concentration in the air phase (µg m^{-3})
C_{in}	inlet formaldehyde concentration in the air phase (µg m^{-3})
A	area of wood sample (m^2)

An exponential regression was then used to determine the formaldehyde emission rate as a function of temperature for each material since previous research has shown that formaldehyde emission rates are related to indoor humidity and temperature (Grot et al. 1985). The use of small test chambers for determining emission rates of materials for a range of environmental conditions has also been well-documented (Molhave 1987; Sanchez et al. 1987; Tichenor 1989). The data from the two plywood samples were combined to obtain a single regression. The measurement data and regression results are shown in Figure 2. These emission rates determined using small chamber tests do not account for absorption with other materials or reactions with other constituents of indoor air that are likely present in an occupied home. Further, these test results do not account for potential reduction of emission rates as materials age.

Real-time formaldehyde measurements using a spectrophotometric monitor were taken in the house over a period of two weeks in December 2015. The sensitivity of the monitor was 0.12 μg m^{-3} with a one second sampling time. Polytetrafluoroethylene sampling tubes were used to deliver air from the basement, living room, master bedroom, and attic to an automatic seven-port sampling valve having a common port to the monitor. Detailed discussion on the real-time formaldehyde measurements can be found in Poppendieck et al. (2016).

Ventilation system airflow rates were measured using a low-flow balometer. Measurements included heat pump supply and return, HRV supply and return, range hood exhaust, and dryer vent exhaust. Airflow measurements, along with other model input values, are provided in Table 2.

Blower door tests were performed to measure the building envelope leakage rate with the HRV outside air and exhaust vents sealed. The building envelope leakage rate was 803 m^3 h^{-1} at 50 Pa (Ng et al. 2015). To more accurately model the airflow and contaminant transport through the building envelope and between zones, a series of blower door tests were performed to estimate the leakage areas of internal partitions and other airflow paths in the house. Multiple test configurations were utilized to determine the leakage areas of the desired control volume as shown in Figure 3. For instance, when determining the whole-house building envelope airtightness, the basement, 1F and 2F floors, and attic constituted the control volume (Figure 3a) by opening the attic and basement doors (shown as ovals) and the blower door was placed in the front door (shown as a blue arrow).

To determine the air leakage between the living area (combined 1F and 2F) and the basement, the blower door was placed in the opening of the basement door (Figure 3c). The control volume was, in this case, the basement. The leakage through the 2 m^2 of exposed basement wall was deducted from the test result in order to isolate only the leakage between the living area and the basement. It was assumed that the leakage area of the basement wall, on a per surface area basis, was the same as the leakage area of the entire building envelope.

The leakage area of the floor between 1F and 2F was not measured because the two-story foyer encompassing the staircase essentially makes 1F and 2F a single zone. However, for both airflow and thermal modeling purposes, 1F and 2F were considered to be separate zones with a relatively large stairway opening between them. The leakage area of the transfer grilles between the basement and living area was determined by taking the difference between the leakage areas measured with and without the grilles sealed, using the control volumes in Figure 3b and 3c.

It was assumed that the leakage area of the roof, on a per surface area basis, was the same as the leakage area of the entire building envelope. Thus, the leakage area of the roof was calculated and subtracted from the result of the test in Figure 3d to determine the leakage area of the attic floor. The leakage area of the transfer grilles between the attic and the living area was determined by taking the difference between the leakage areas measured with and without the grilles sealed, using the control volume in Figure 3d. Calculated leakage areas are provided in Table 2.

Simulation Model

To better understand the impact of product selection (i.e., contaminant emission rates) and outdoor air ventilation rates on building energy use and IAQ, specifically formaldehyde and acetaldehyde, a coupled thermal-airflow model of the house was developed. In the past, the airflow and thermal models were independent and the interactions between temperature and airflow could not be fully captured. In this paper, the coupled-model provides the ability for an airflow model to co-simulate, i.e., exchange parameters such as airflow rates and temperatures, with a thermal model. The coupled model allows the user to evaluate the effects of various design decisions and building features on indoor air quality and energy use at the same time. The model was verified, as presented below, using measured energy use and real-time formaldehyde concentration measurements. The verified model was then used to simulate the energy use and indoor concentrations of formaldehyde and acetaldehyde for different outdoor air ventilation rates.

This modeling was performed using a whole-building multizone airflow and IAQ analysis tool, CONTAM, coupled with EnergyPlus (Dols et al. 2015), a whole-building energy analysis tool (DOE 2015b). CONTAM accounts for the interaction between external forces driving airflow (inside-outside temperature difference and wind) and building HVAC system airflow rates to determine pressures and airflows across internal partitions and the building envelope, i.e., interzone airflows and infiltration/exfiltration rates. CONTAM also accounts for external and internal contaminant sources and removal mechanisms to calculate contaminant transport associated with the previously determined airflows. EnergyPlus implements a multizone heat transfer model that accounts for conductive, convective and radiant heat transfer associated with building materials (e.g., walls, floors, ceilings and windows); interzone and envelope airflows; and HVAC systems. CONTAM requires the user to define zone air temperatures while EnergyPlus requires the user to define infiltration and interzone airflow rates. Recent enhancements to both programs enable the use of co-simulation to perform run-time coupling between them in a quasi-dynamic manner (Dols et al. 2016; Wetter 2011). During co-simulation, indoor air temperatures and HVAC system airflow rates are passed from EnergyPlus to CONTAM, and airflow rates across the building envelope and between internal zones are passed from CONTAM to

EnergyPlus. These coupled simulations thereby account for wind-driven, stack-driven and ventilation system-driven infiltration and ventilation using measurements of actual envelope leakage characteristics and HVAC system airflows.

The NZERTF was idealized as a five zone building consisting of one zone for each floor and two attic spaces, a main attic above the second floor and a smaller one above the living room on the east side (see Figure 1). Model inputs were determined based on building design information and the aforementioned measurements. The measured envelope leakage was distributed uniformly over the entire above-grade building envelope, using a value of 0.48 $cm^2 \cdot m^{-2}$ at 4 Pa in the model for the effective leakage area. Details of the conversion of fan pressurization test results to leakage areas can be found in ASHRAE (2017). Average measured airflow and emission rates are listed in Table 2. The E_{AS} for acetaldehyde was 7.4 $\mu g\ h^{-1} \cdot m^{-2}$. The formaldehyde emission rate was based on the air temperature dependent emission rate measurements presented previously (Figure 2) and in the model applied to the surface areas in Table 3. The outdoor concentration of formaldehyde and acetaldehyde concentrations were both modeled at a constant 0.8 $\mu g\ m^{-3}$, assuming no losses or filtration through the exterior building envelope or through the HRV.

Model Verification

Prior to coupling, an EnergyPlus model of the NZERTF, including all of the systems and internal loads, was developed and validated with measured electricity and water usage data by Kneifel et al. (2015). This EnergyPlus model was then used to develop the EnergyPlus representation within the coupled CONTAM-EnergyPlus model used in this study. Two verification simulations were performed using weather data from an Actual Meteorological Year (AMY) weather file for the Montgomery County Airpark (KGAI) weather station (Weather Analytics 2014), located about 11 km from the NIST campus. First, the energy performance of the coupled model was evaluated and secondly, contaminant transport analysis was verified against real-time formaldehyde measurements.

Energy performance simulation results were compared to measurements made from July 2013 to June 2014 (Fanney et al. 2015). Simulated and measured annual heating, cooling, and total energy use compared favorably as shown in Figure 4. The simulated annual house energy consumption (13 421 kWh) was 4 % more than the measured energy consumption (12 859 kWh).

In the second verification simulation test, real-time formaldehyde measurements were taken more than a year after the 15 months of periodic measurements. The operation of the HRV was changed to be intermittent, which yielded a ventilation rate approximately 25 % less than the NZERTF ventilation rate of 171 $m^3 \cdot h^{-1}$ (0.11 h^{-1}).

Formaldehyde emissions were modeled using the chamber measurement results shown in Figure 2. The simulated and measured concentrations over two weeks are shown in Figure 5. The average and standard deviation of the simulated and measured concentrations for the basement, combined 1F and 2F, and attic of the NZERTF are summarized in Table 4. The simulated and measured formaldehyde concentrations follow similar trends and are of the same magnitude in all of the zones. Since the modeled and measured concentrations are in good agreement, it can be concluded that a temperature-dependent formaldehyde emission model is sufficient for the NZERTF. The simulated concentrations (lines) are smoother than the measured concentrations because the HRV was modeled as operating continuously but was actually operating on an intermittent schedule (on for 40 min then off for 20 min).

The simulated concentrations in the basement were higher than measured, especially for the second week of measurements (Figure 5b and Table 4). In contrast, the simulated concentrations in the combined 1F and 2F were lower than measured, and the simulated concentrations in the attic were similar to the measurements. The differences in the measured and simulated basement and combined 1F and 2F concentrations could be attributed in part to how the HVAC system was modeled. In reality, the HVAC system is a single system with supplies serving the basement, 1F and 2F, and returns located on 1F and 2F but not in the basement. In contrast, the EnergyPlus model implements a balanced (for each zone) HVAC system, so it includes a return located in the basement that likely impacts the airflow between the basement and 1F.

Higher simulated concentrations than those measured in the basement could be attributed to several factors. The balanced system model may result in less mixing between 1F and the basement. Therefore, the air from 1F, having lower concentrations of formaldehyde due to dilution of outdoor air via the HRV and infiltration, did not dilute the basement air in the model. Future work will address modeling of unbalanced HVAC systems in the context of coupling EnergyPlus with CONTAM. Another difference between the actual NZERTF and the model relates to fan operation of the heat pump. The actual fan cycles on and off during operation when thermostat setpoints are met. In contrast, the airflow rate of the EnergyPlus fan varies widely between minimum and maximum airflow rates and never shuts off completely due to the fan operating mode of the EnergyPlus unitary air-to-air heat pump model.

There may also be sources of formaldehyde not accounted for, such as in the exterior walls and composite wood structural members, that may have led to differences between the measured and simulated concentrations. Despite these differences, the measured and simulated concentrations tended to agree well, so the model was considered adequate to evaluate the effects of different outdoor air ventilation rates on indoor concentrations and energy use.

Simulations

Having characterized the performance of the coupled model, the model was used to evaluate indoor concentration of both formaldehyde and acetaldehyde on an annual basis. In order to evaluate the effects of different outdoor air ventilation rates on indoor concentrations of formaldehyde and acetaldehyde and energy use, the following five levels of outdoor air ventilation rate were simulated: HRV off, 137 m^3 h^{-1} (0.09 h^{-1}) (ASHRAE Standard 62.2-2010 minimum requirement), 171 m^3 h^{-1} (0.11 h^{-1}) (NZERTF ventilation rate), 280 m^3 h^{-1} (0.18 h^{-1}) (ASHRAE 62.2-2013 minimum requirement), and a higher rate of 525 m^3 h^{-1} (0.35 h^{-1}) that was selected to reduce formaldehyde and acetaldehyde below harmful, noncancerous benchmark levels (RfC and cREL values in Table 1). The modeled HRV fan power was adjusted to reflect the change in airflow rate from the NZERTF ventilation rate case, but no other changes to the input parameters were made. Even when the HRV is off, CONTAM will calculate an outdoor air change rate, because infiltration may still occurs due to natural driving forces.

For all of the ventilation rate cases, simulations were performed using a Typical Meteorological Year 3 (TMY3) weather file for Baltimore, MD (NREL 2015), which represents typical weather over a longer time period, e.g., 30 years. The use of TMY3 weather is suitable for what-if studies because the data represents typical weather rather than extreme conditions.

Results and Discussion

The energy use consequences and concentrations of formaldehyde and acetaldehyde resulting from the five outdoor air ventilation rates are compared in Figure 6. The figure shows the simulated annual average formaldehyde (black squares) and acetaldehyde (white circles) concentrations, averaged over the 1F and 2F, for the five outdoor air ventilation rates as a function of the total simulated energy use. The ventilation rates are plotted as triangles and the values are on the right axis. The formaldehyde and acetaldehyde health references are shown as horizontal red lines. Table 5 shows the 90th percentile and maximum concentrations for combined 1F and 2F and the attic.

The simulated PV production using typical weather data (15 730 kWh) is shown as a dotted vertical green line, i.e., the NZE level. Figure 6. All but the highest ventilation rate case yielded simulated total energy consumption below the simulated NZE value. This indicates that the NZERTF could have been ventilated at a rate even greater than that required by ASHRAE 62.2-2013 (0.18 h^{-1}) and still meet NZE goals, as simulated by the coupled CONTAM-EnergyPlus model using typical weather data.

Formaldehyde

Despite source control measures to minimize the use of building products with urea-formaldehyde resin, none of the simulated ventilation rates reduced formaldehyde concentrations below levels associated with a cancer risk of 1 in 1 000 000 (0.08 µg m^{-3}). This is due to many factors, but the primary reason is that, like most locations in the United States (EPA 2017), the average outside concentration of formaldehyde measured at the NZERTF was above this concentration. As will be discussed later, studies of other new homes also found formaldehyde above the level associated with a cancer risk of 1 in 1 000 000.

Ventilating at the NZERTF rate of 171 m^3 h^{-1} (0.11 h^{-1}) resulted in the simulated NZERTF annual average formaldehyde concentration of 6.2 µg m^{-3} in the combined 1F and 2F, which is 22 % lower than the formaldehyde concentration associated with a cancer risk of 1 in 10 000 (8.0 µg m^{-3}) and 31 % lower than the OEHHA cREL (9.0 µg m^{-3}).

The ASHRAE 62.2-2010 rate of 137 m^3 h^{-1} (0.09 h^{-1}) would be 25 % below the NZERTF ventilation rate of 171 m^3 h^{-1} (0.11 h^{-1}). Ventilating lower at the ASHRAE 62.2-2010 rate resulted in a 18 % increase in the simulated annual average formaldehyde concentration (from 6.2 µg m^{-3} to 7.3 µg m^{-3}). This concentration is still 9 % lower than the concentration associated with a cancer risk of 1 in 10 000 (8.0 µg m^{-3}) and 19 % lower than the OEHHA cREL of 9.0 µg m^{-3}. This lower ASHRAE 62.2-2010 ventilation rate (0.09 h^{-1}) yielded a simulated annual energy savings of 4 % compared with ventilating 25 % more at the NZERTF rate (0.11 h^{-1}).

An outdoor ventilation rate of 0.35 h^{-1} would be three times higher than the NZERTF ventilation rate. This resulted in a 55 % reduction in the simulated average formaldehyde concentration (2.8 µg m^{-3}). This concentration is below both the formaldehyde concentration associated with a cancer risk of 1 in 10 000 (8.0 µg m^{-3}) and the OEHHA cREL (9.0 µg m^{-3}). Tripling the ventilation rate to 0.35 h^{-1} would result in an annual simulated energy use increase of 38 % compared with ventilating at the NZERTF ventilation rate.

As summarized in Table 5, the maximum simulated formaldehyde concentration in the attic could reach 123 µg m^{-3} when the HRV is operating (i.e., all but the HRV off case), which was 15 times higher than the formaldehyde concentration associated with a cancer risk of 1 in 10 000 (8.0 µg m^{-3}) and 13 times higher than the OEHHA cREL (9.0 µg m^{-3}). For the HRV off case, the concentrations were as high as 151 µg m^{-3} in the attic and 100 µg m^{-3} in the combined 1F and 2F. It should be noted that the maximum concentrations reached in the attic for all of the cases when the HRV was operating (i.e., all but the HRV off case) are all about 123 μg m^{-3}, which implies that increasing the ventilation in the occupiable areas did not impact the concentrations in the passively ventilated spaces.

Acetaldehyde

While low emission building products were specified for the construction of the NZERTF, acetaldehyde was not specifically targeted. Like formaldehyde, none of the simulated ventilation rates reduced acetaldehyde concentrations below levels associated with a cancer risk of 1 in 1 000 000 (0.5 μg m^{-3}). At the NZERTF ventilation rate of 137 m^3 h^{-1} (0.11 h^{-1}), the simulated annual average acetaldehyde concentration was 16.5 μg m^{-3}, which is below the concentration associated with a cancer risk of 1 in 10 000 (50 μg m^{-3}) and the OEHHA cREL (140 μg m^{-3}), but above the EPA RfC (9.0 μg m^{-3}). The outdoor air ventilation rate required to bring the levels of acetaldehyde concentrations below the EPA RfC (9.0 μg m^{-3}) would be between the ASHRAE 62.2-2013 rate (0.18 h^{-1}) and 0.35 h^{-1} with an associated energy increase between 14 % and 38 % for the weather file employed in this analysis. At a ventilation rate of 0.35 h^{-1}, the model predicts the house would no longer achieve NZE use for the year as operated, i.e. heating and cooling with an air-to-air heat pump and ventilating continuously with the HRV.

Without any mechanical outdoor air ventilation, the indoor concentrations of formaldehyde and acetaldehyde would be six times higher than the concentration associated with the NZERTF rate, with an associated 17 % reduction in annual simulated energy use.

Discussion

The yearly average simulated formaldehyde concentration (6.2 μg m^{-3}) at the NZERTF ventilation (0.11 h^{-1}) was lower than 13 newly constructed, occupied homes designed to meet EPA Indoor airPlus guidelines (Hult et al. 2015), and all but two of 108 occupied, new standard construction homes in California (Offermann 2009). This was true despite the fact that the NZERTF ventilation rate was less than half of the average outdoor ventilation rate measured in the homes in the Hult (0.26 h^{-1}) and Offermann studies (0.24 h^{-1}). It should be emphasized that the NZERTF is unoccupied and unfurnished, whereas the home in the Hult and Offermann studies were furnished and occupied. In terms of acetaldehyde, the simulated annual average concentration (16.5 μg m^{-3}) was above the EPA RfC (9.0 μg m^{-3}). Roughly 65 % of the 108 California homes had acetaldehyde concentrations higher than the EPA RfC value (Offermann 2009).

The average effective formaldehyde emission rate modeled in a previous simulation study conducted by the authors was 5.1 μg h^{-1} m^{-2} (Ng et al. 2016). This emission rate was based on whole-house concentrations normalized over the 1F, 2F, and the attic. The formaldehyde emission rates used in the present study were based on laboratory measurements (Figure 2). Taking the volume-weighted concentrations simulated in each zone and dividing by the same floor area yielded a formaldehyde emission rate of 4.0 μg h^{-1} m^{-2}. The difference in these two surface-averaged emission rates could be due to several factors. The 20 % difference between the two emission rates indicate that the emissions from the flooring, plywood and cabinets account for the majority of formaldehyde in the NZERTF. Discrepancies in properly accounting for all of the wood sources and neglecting the air-side resistance of emission modeling could also lead to differences. Other sources of formaldehyde in the house (e.g., heterogenous and homogenous reactions and other materials) not accounted for in the model could also lead to differences in these overall emission rates.

In studies of homes comparable to the NZERTF, the average effective formaldehyde emission rate, normalized over the living spaces, were 24.4 μg h^{-1} m^{-2} and 11.0 μg h^{-1} m^{-2}, respectively in Hult et al. (2015) and Offermann (2009). Normalizing the simulated annual average formaldehyde concentration in the NZERTF over only 1F and 2F (excluding the attic), ventilating at the NZERTF rate (0.11 h^{-1}) and using the actual weather file, resulted in a lower average effective formaldehyde emission rate of 5.8 μg h^{-1} m^{-2}. Since the NZERTF is unfurnished and unoccupied, the lower effective formaldehyde emission rate at the NZERTF could be attributed to sources that are present in the other homes, but not present at the NZERTF. Such sources include, but are not limited to furniture, cleaning products, air fresheners, permanent-press fabrics, and reaction products of ozone and volatile organic chemicals released indoors (Salthammer et al. 2010).

As mentioned above, the differences between the actual and modeled heat pump systems (i.e., the imbalance of the system flows on each floor of the NZERTF) may not affect the energy performance; however, the differences in system configurations may influence the internal airflow patterns and thus indoor temperature and contaminant concentrations. Therefore, future investigations into the system representations in the coupled-model need to be performed in order to consider these differences.

This study demonstrates the need for source control in homes with relatively airtight envelopes. At the NZERTF, controlling for formaldehyde emissions was a key design objective, leading to concentrations roughly four times less than in other new homes. However, the NZERTF was unfurnished and occupied only during maintenance or tours.

Hence, the data presented in this paper only account for the emissions attributed to the building materials. Occupants in real homes will likely introduce formaldehyde and acetaldehyde through furniture, and secondary ozone reactions with household products, personal care products and secondary reactions with their skin oils (Salthammer et al. 2010). Hence, based on current knowledge, when establishing building ventilation rates, emissions from building products should only be considered as one among the many other potential sources that should be accounted for when designing and operating buildings.

CONCLUSION

The NIST NZERTF was constructed to support the development and adoption of cost-effective NZE designs and technologies, and to demonstrate that net-zero could be achieved while meeting the needs and comfort of occupants. To support these objectives, building material source control approaches were implemented to minimize the use of products with urea-formaldehyde resin and to utilize products with relatively low VOC emissions. Indoor and outdoor measurements of formaldehyde and acetaldehyde as well as direct laboratory emission measurements were used to establish emission rate inputs for a coupled CONTAM-EnergyPlus model of the house. The model was also used to study the effect of a range of outdoor air ventilation rates on the indoor concentrations of formaldehyde and acetaldehyde and on annual energy use. None of the ventilation rates reduced formaldehyde and acetaldehyde concentrations below the concentrations associated with a cancer risk of 1 in 1 000 000, the lower risk level used by the EPA for air toxics in outdoor air, because the outdoor formaldehyde and acetaldehyde concentrations (based on measurements presented herein and used in the model) were both above these EPA risk levels. In contrast, all simulated ventilation rates at or greater than the existing NZERTF rate would result in acetaldehyde and formaldehyde concentrations lower than those associated with a cancer risk of 1 in 10 000. At the NZERTF ventilation rate, the simulated average concentration of formaldehyde on the first and second floors was 6.2 μg m^{-3}, which is 31 % lower than the OEHHA cREL of 9 μg m^{-3}, a health benchmark below which there are deemed to be no harmful, noncancerous impacts. However, to remain below the nonharmful, noncancerous effects from acetaldehyde exposure (EPA RfC of 9 μg m^{-3}), the building outdoor air ventilation rate would have to be between the ASHRAE 62.2-2013 rate and a rate triple the NZERTF rate, with an associated annual energy increase of between 14 % and 38 %. At a ventilation rate of 0.35 h^{-1}, the NZERTF would no longer achieve NZE operation for the typical weather conditions modeled.

This study demonstrated that selecting outdoor air ventilation rates for a residence can be complex. Lower outdoor air ventilation rates can lead to lower energy use but result in increased levels of indoor contaminants. Increasing the outdoor air ventilation rate to meet health benchmarks is also not straightforward. If the IAQ design target is to maintain indoor concentrations below noncancerous impact levels (cREL), but not achieve concentrations inhibiting chronic effects, increased outdoor air ventilation rates may come at the loss of NZE operation. An IAQ design target of an acceptable cancer risk of 1 in 1 000 000 may be difficult to achieve by diluting indoor air with outdoor air ventilation for some chemicals, such as formaldehyde, especially if the outdoor concentration of the contaminant is already higher than this level. An IAQ design target of an acceptable cancer risk of 1 in 10 000 may be achievable from a ventilation standpoint, but poses a greater potential carcinogenic risk to the occupants.

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Table 1. Summary of Health References				
Contaminant	IARC Designation	Agency/Reference	Type	Concentration
Acetaldehyde	Probable Human Carcinogen	EPA (1988)	1 in 1 000 000 cancer risk	0.5 μg m^{-3}
		EPA (1988)	1 in 10 000 cancer risk	50 μg m^{-3}
		EPA (2000)	RfC	9 μg m^{-3}
		OEHHA (2016)	cREL	140 μg m^{-3}
Formaldehyde	Human Carcinogen	EPA (1989)	1 in 1 000 000 cancer risk	0.08 μg m^{-3}
		EPA (1989)	1 in 10 000 cancer risk	8 μg m^{-3}
		OEHHA (2016)	cREL	9 μg m^{-3}

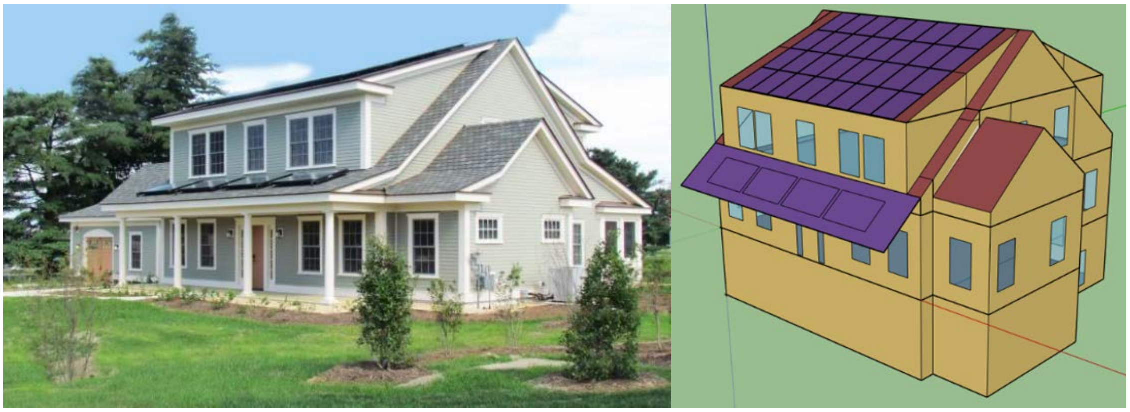
1. RfC is the EPA inhalation reference concentration below which there are deemed to be no harmful noncancerous impacts
2. cREL is the California OEHHA chronic relative exposure level (cREL) below which there are deemed to be no harmful noncancerous impacts

Table 2. Summary of Inputs in Coupled CONTAM-EnergyPlus Model of NZERTF	
Input	**Value**
Heat pump max airflow	1500 m^3 h^{-1}
HRV average supply and exhaust airflow	171 m^3 h^{-1}
Kitchen range hood airflow	180 m^3 h^{-1}
Dryer exhaust airflow	60 m^3 h^{-1}
Building envelope airtightness	0.48 cm^2 m^{-2} at 50 Pa, n = 0.67
Floor leakage between basement and 1F and between 1F and 2F	4.05 cm^2 m^{-2} at 50 Pa, n = 0.50
Floor leakage between 2F and attic	4.66 cm^2 m^{-2} at 50 Pa, n = 0.50
Leakage area of transfer grilles between basement and 1F	225 cm^2 at 50 Pa, n = 0.50
Leakage area of transfer grilles between 2F and attic	232 cm^2 at 50 Pa, n = 0.50
Acetaldehyde emission	7.4 μg h^{-1} m^{-2}

Table 3. Wood Products and Associated Surface Areas	
Wood Product	**Surface Area (m^2)**
Wood flooring	1F = 151 2F = 130
Plywood	Basement ceiling = 151 Attic exposed areas = 116
Cabinetry	Total on 1F and 2F = 81

Table 4. Comparison of measured and simulated formaldehyde concentrations for a 2-week measurement period in December 2015				
Area(s) of NZERTF	**Measured Average (μg m^{-3})**	**Measured Standard Deviation (μg m^{-3})**	**Simulated Average (μg m^{-3})**	**Simulated Standard Deviation (μg m^{-3})**
First week				
Basement	6.7	0.7	7.2	0.2
1F, 2F	6.8	0.8	6.0	0.3
Attic	18.7	1.3	17.8	2.0
Second week				
Basement	8.6	1.1	10.5	0.4
1F, 2F	9.1	1.4	6.5	0.2
Attic	26.7	4.0	28.8	5.2

Table 5. Comparison of simulated formaldehyde concentrations for 5 ventilation rates					
	HRV off ($0.00\ h^{-1}$)	**62.2-2010 ($0.09\ h^{-1}$)**	**NZERTF ($0.11\ h^{-1}$)**	**62.2-2013 ($0.18\ h^{-1}$)**	**$0.35\ h^{-1}$**
	1F, 2F				
90^{th} percentile ($\mu g\ m^{-3}$)	71.1	10.6	8.7	5.8	3.6
Maximum ($\mu g\ m^{-3}$)	100.1	16.5	14.4	10.7	7.3
	Attic				
90^{th} percentile ($\mu g\ m^{-3}$)	104.3	80.5	79.8	78.4	77.6
Maximum ($\mu g\ m^{-3}$)	151.4	123.3	123.0	123.3	123.3



(a) (b)

Figure 1 **(a) Photograph of NZERTF and (b) Three-dimensional representation of NZERTF EnergyPlus Model**

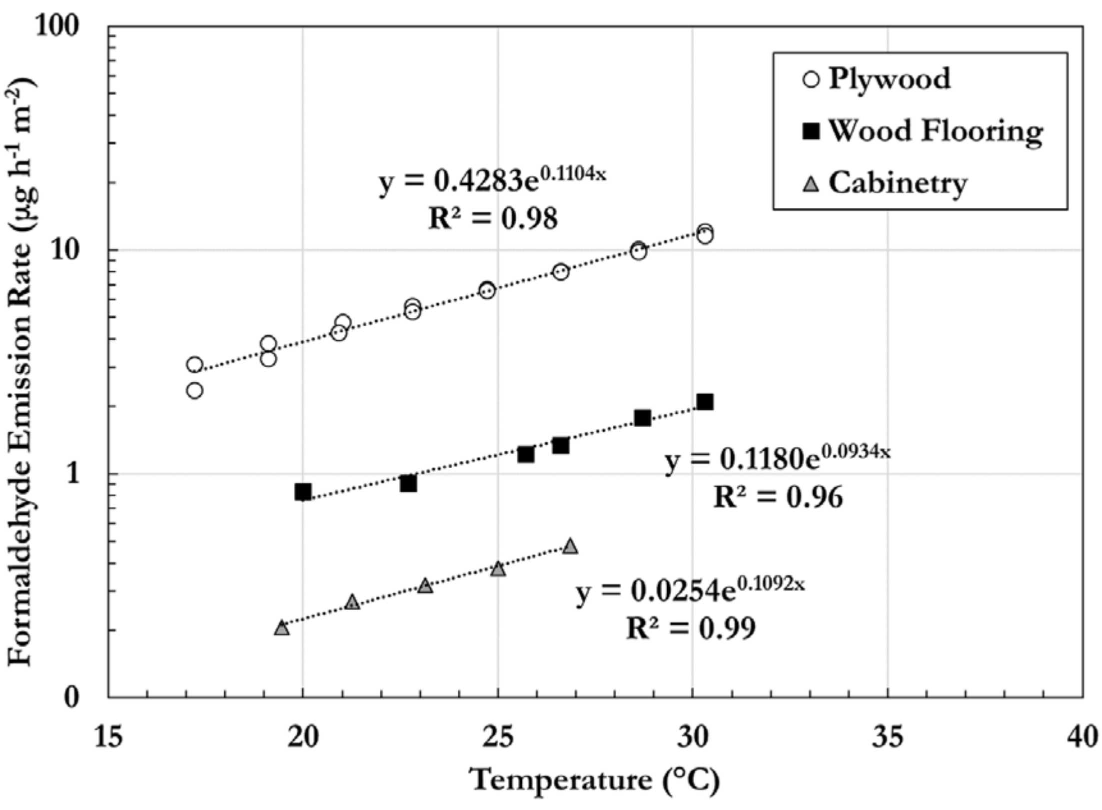


Figure 2 **Formaldehyde emissions of three wood products in the NZERTF**

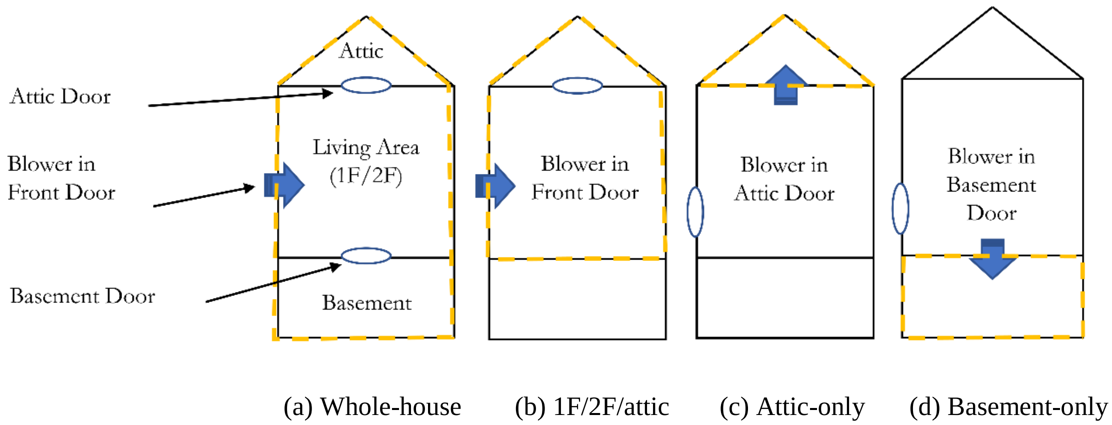


Figure 3 **Schematic of blower door tests with various control volumes**

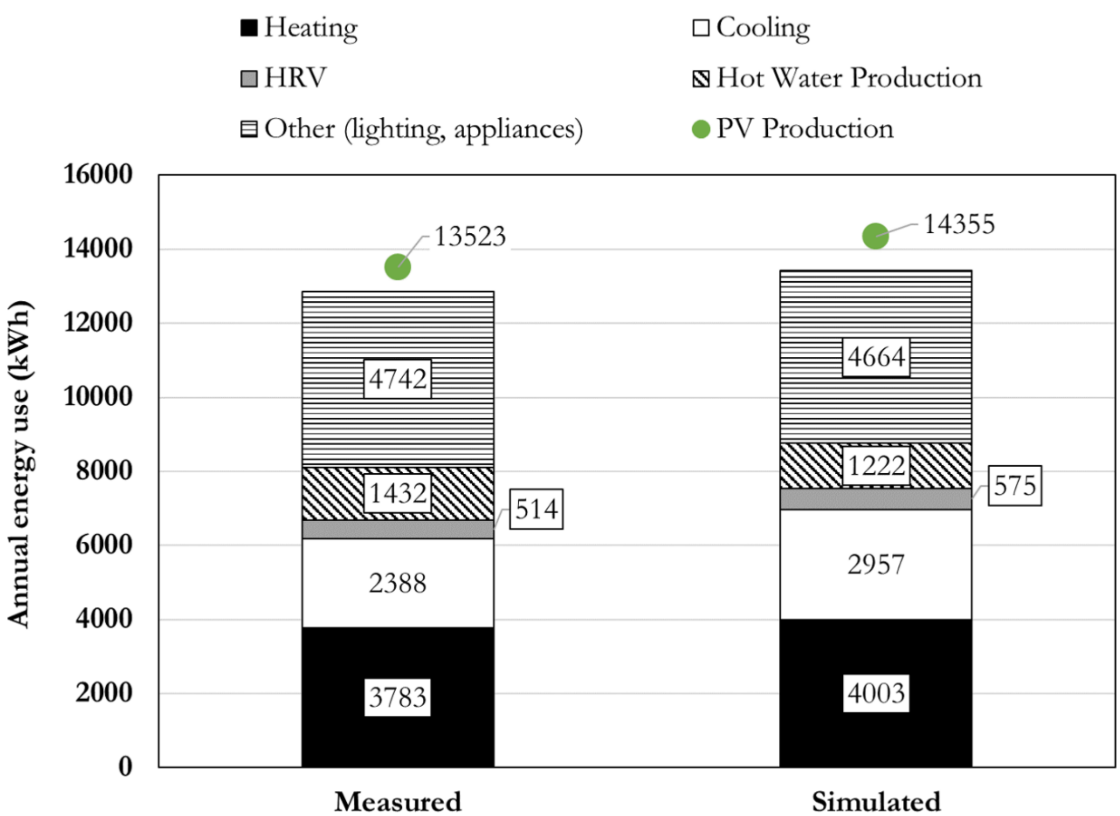
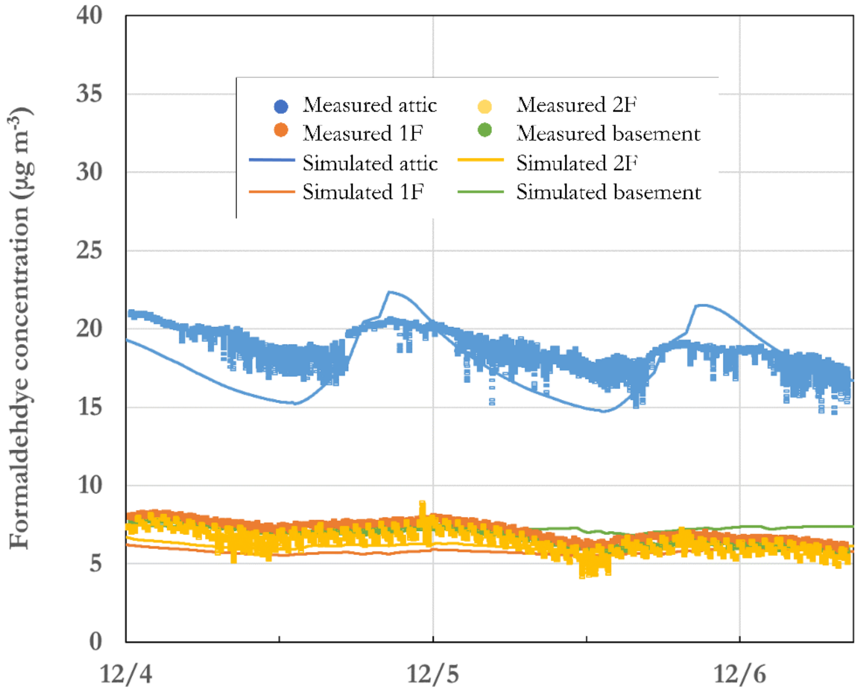
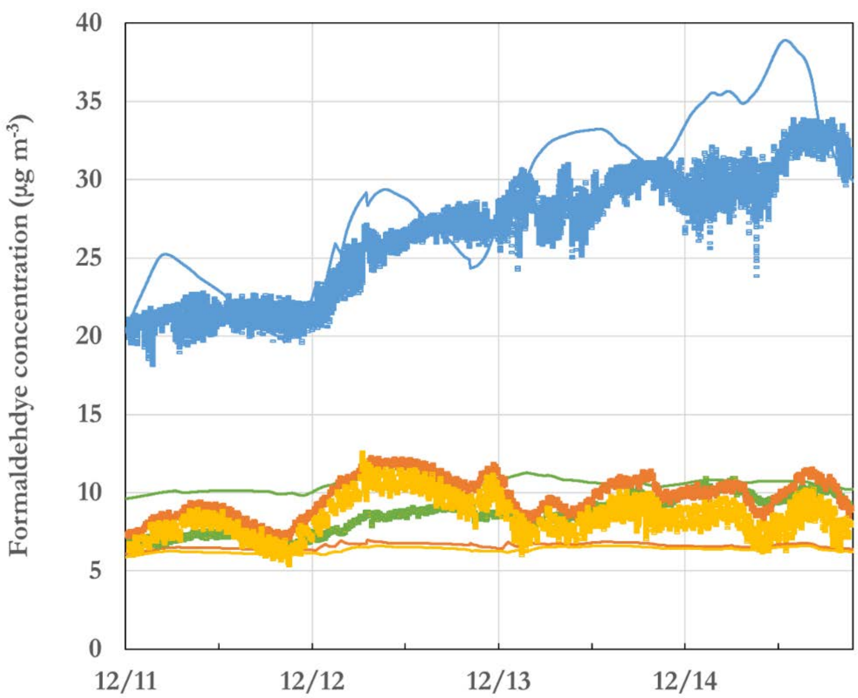


Figure 4 **Comparison of measured and simulated annual energy use and PV production for July 2013-June 2014**



(a)



(b)

Figure 5 Real-time and simulated formaldehyde concentration data from two sampling sessions. (a) Average outdoor temperature was 3.5 °C (b) Average outdoor temperature was 12.7 °C. Average wind speed (both sessions) was 0.9 m s^{-1}

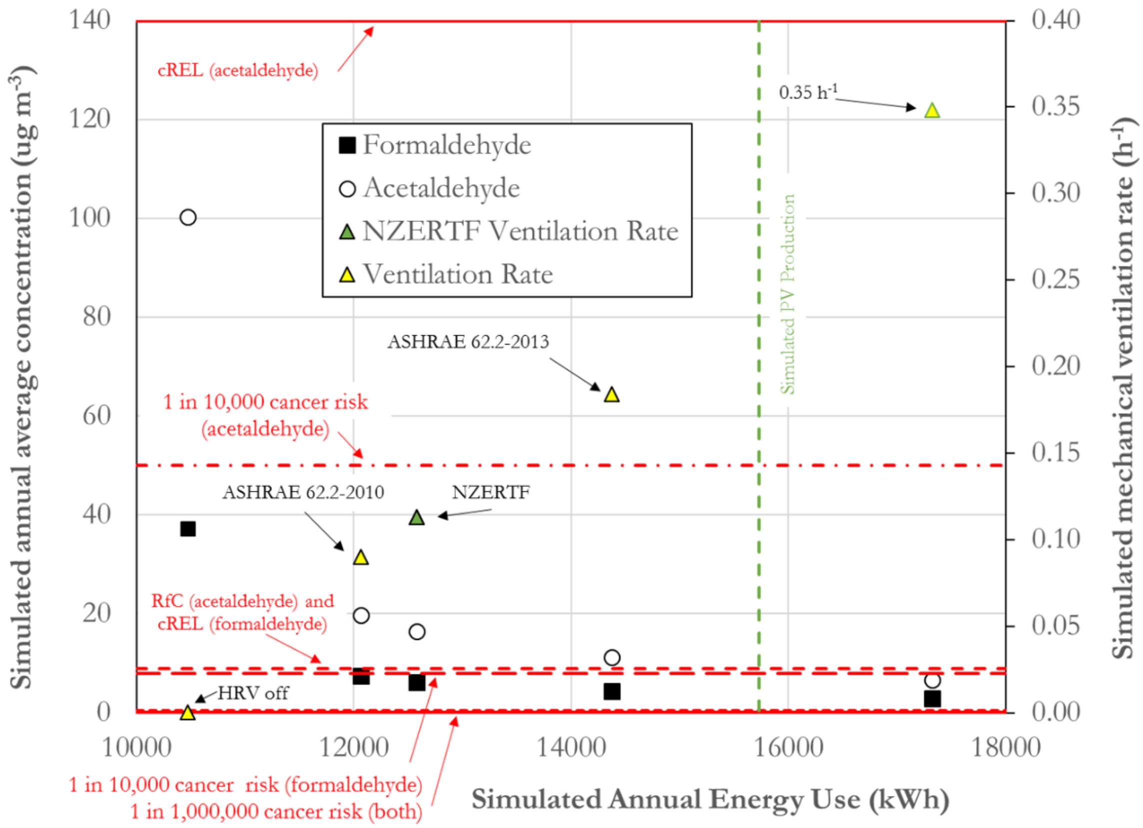


Figure 6 Simulated annual average formaldehyde and acetaldehyde concentrations for five ventilation rates and their associated simulated annual energy consumption