Evaluating IAQ and Energy Impacts of Ventilation in a Net-Zero Energy House Using a Coupled Model

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ABSTRACT

The National Institute of Standards and Technology (NIST) constructed the Net-Zero Energy Residential Test Facility (NZERTF) to support the development and adoption of cost-effective NZE designs and technologies. Among the key objectives of the facility design was creating a healthy and comfortable environment for the assumed occupants by providing adequate outdoor air ventilation and reducing indoor contaminant sources. Building material source control guidelines were implemented to minimize the use of products with urea-formaldehyde resin and to utilize products with relatively low volatile organic compound (VOC) emissions. Indoor and outdoor concentrations of formaldehyde and acetaldehyde were measured approximately monthly during two years of house operation. Real-time formaldehyde concentration and energy measurements were also used to validate the indoor air quality (IAQ) and energy predictions of a coupled CONTAM-EnergyPlus model of the house. The validated model was then used to evaluate the IAQ and energy impacts of different outdoor air ventilation rates. The results of this work demonstrate the need for appropriate product selection (source control) and 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). Thus, goals for achieving net-zero energy performance have been established in the United States and around the world (City of Melbourne 2014; EPBD 2010; IEA 2014). A net-zero energy building (ZEB) is an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy (DOE 2015a).

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 net-zero energy (NZE) designs, technologies, and construction methods. The two-story house shown in Figure 1 has a basement and attic, and is similar in size (242 m^2 of occupied floor area, with 485 m^2 inside the building envelope including the attic and basement) and aesthetics to homes in the surrounding communities. The house is unoccupied and not furnished other than permanently installed cabinetry.

Many technologies are employed in the house to achieve the NZE goals including a 10.2 kW photovoltaic (PV) system, a high efficiency air-to-air heat pump, a solar hot water system, and a heat recovery ventilator (HRV). All floors of the house, including the attic, are within the conditioned space. A central heat pump system provides supply air to all floors except the attic. Passive air transfer grilles connect the basement to the first floor and 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 and ducted HRV system supplies outdoor air to the first floor kitchen and second floor bedrooms, while drawing 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 in the ASHRAE Standard 62.2-2010 (ASHRAE 2010), the HRV was sized to deliver 137 $m^3\ h^{-1}$ of outdoor air, but actually delivered 171 $m^3\ h^{-1}$ based on the available fan speeds in the unit. This rate did not include any infiltration credit. More information on the NZERTF design can be found in Pettit et al. (2014).

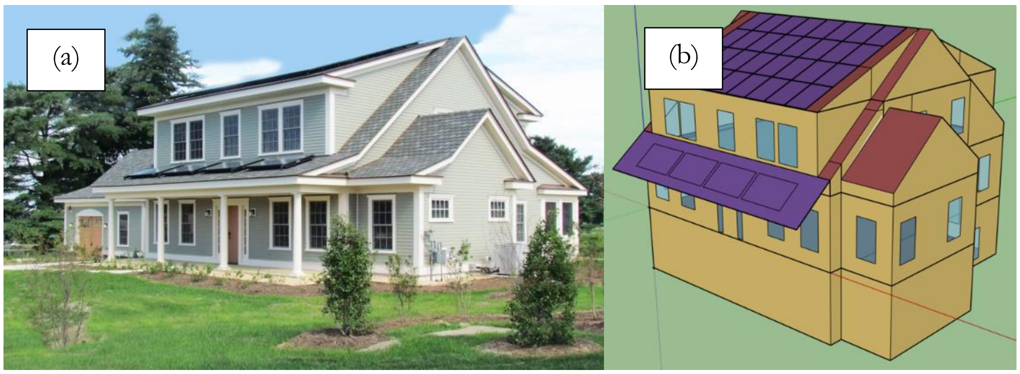

Figure 1 (a) Photograph of NZERTF and (b) Three-dimensional representation of NZERTF EnergyPlus Model

The pursuit of net-zero energy is often done with little or no verification of the achievement of acceptable indoor air quality (IAQ). Teichman et al. (2015) reviewed 100 cases studies of high performance buildings and found 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 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 air change rates are not adequate or if chemicals are emitted that are not captured in the emissions testing.

The NZERTF was built minimizing use of products with urea-formaldehyde resin and with products that had low emissions of VOC. The guidelines for the building product selection and construction best practices for IAQ used at the NZERTF are available as architectural specifications in Bernheim and Hodgson (2014). After construction of the home, indoor and outdoor concentrations of formaldehyde and 30 other VOCs were measured approximately monthly during two years of house operation, and the results reported in Poppendieck et al. (2015). Formaldehyde emission factors in the NZERTF are on average at least four times lower than comparable houses. However, NZERTF concentrations of some VOCs are higher than comparable houses with 20 % higher air change rates (Ullah et al. 2016).

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 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 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 for example eye, nose or throat irritation. California Office of Environmental Health Hazard Assessment (OEHHA) chronic relative exposure level (cREL) and the EPA inhalation reference concentration (RfC) are both concentrations below which there are deemed to be no deleterious noncancerous impacts. These values are also summarized in Table 1.

To better understand the impact of product selection (i.e., contaminant emission rates) and outdoor air ventilation rates on building energy use and IAQ, a coupled thermal-airflow model of the house was developed. The model was validated using measured energy use and real-time formaldehyde concentration measurements. The validated model was then used to simulate the energy use and indoor concentrations of formaldehyde and acetaldehyde for different outdoor air ventilation rates.

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}

SIMULATION MODEL

Modelling of the NZERTF was performed using the whole-building multizone airflow and indoor air quality software CONTAM (Dols et al. 2015) coupled with EnergyPlus, a whole-building energy analysis software (DOE 2015b). CONTAM accounts for the interaction between external driving forces (ambient temperature and wind) and internal mechanisms (building heating, ventilating, and air-conditioning (HVAC) system airflows) to determine resultant pressures and airflows across internal and external building partitions, i.e., interzone airflows and infiltration/exfiltration rates. CONTAM can also account 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 infiltration airflows; and HVAC systems. CONTAM requires the user to define zone air temperatures while EnergyPlus requires the user to input infiltration and interzone airflow rates. Recent enhancements to both programs enable run-time coupling between them in a quasi-dynamic manner (Dols et al. 2016; Wetter 2011). During coupled simulations, indoor temperatures and HVAC system flow 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 rates based upon measurements of actual envelope leakage characteristics and HVAC system airflow rates.

The NZERTF was modelled as a five zone building consisting of one zone for each floor and two attic spaces, a main one 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 measurements as follows. Ventilation system airflow rates were measured; including heat pump supply and return, HRV supply and return, range hood, and dryer vent exhaust. Average measured rates were input into the CONTAM-EnergyPlus model. Emission rates in this study are effective emission rates that combine emission and removal mechanisms. The average effective, occupied floor area (1st floor and 2nd floor) formaldehyde emission rate over one year (6.7 μg h^{-1} m^{-2}) was measured using one hour 2,4-dinitrophenylhydrazine (DNPH) cartridge sampling according to ASTM D5197 (ASTM 2009) and was reported in Poppendieck et al. (2015). The effective emission rate accounts for both sources and sinks in the NZERTF. Previous investigations indicated that there was likely no significant source of formaldehyde in the basement, but there are likely sources on other levels. The formaldehyde source was modeled as being present on the 1st, 2nd and attic floors. Hence, the effective floor area formaldehyde emission rate was normalized to include the attic floor area and modeled as 5.1 μg h^{-1} m^{-2} in this study. The average effective acetaldehyde emission rate was normalized and modeled over the basement, 1st, 2nd, and attic floors (7.4 μg h^{-1} m^{-2}). It was assumed that the outside concentration of formaldehyde and acetaldehyde were both 0.0 μg m^{-3} in the model, though measured outdoor formaldehyde and acetaldehyde concentrations were both on average 0.8 μg m^{-3} between November 2013 and March 2014 based on periodic measurements (Poppendieck et al. 2015). All model inputs are listed in Table 2.

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	0.37 cm^2 m^{-2} at 4 Pa
Formaldehyde emission	5.1 μg h^{-1} m^{-2}
Acetaldehyde emission	7.4 μg h^{-1} m^{-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). In the CONTAM model, this envelope leakage was distributed uniformly over the entire above-grade building envelope with an effective leakage area of 0.37 cm^2 m^{-2} at 4 Pa. Details of this conversion can be found in the ASHRAE (2013).

The EnergyPlus model, including all of the systems and internal loads, was developed and validated with measured electrical and water-use data by Kneifel et al. (2015). This EnergyPlus model was then used to develop the EnergyPlus representation of the coupled CONTAM-EnergyPlus model used in this study.

An Actual Meteorological Year (AMY) weather file from July 2013 to June 2014 for the Montgomery County Airpark (KGAI) weather station (Weather Analytics 2014), located about 11 km from the NIST campus, was used in the simulations. The simulated annual heating, cooling, and total energy use predicted by the coupled CONTAM-EnergyPlus model are shown in Figure 2, along with the measured energy use (Fanney et al. 2015). The simulated annual house energy consumption (13 600 kWh) was 5 % more than the measured energy consumption (12 900 kWh). The simulated annual PV production (14 400 kWh) was 6 % more than the measured PV production (13 500 kWh).

Model Validation

Measurements from a real-time spectrophotometric formaldehyde monitor, which were taken approximately one year after the Poppendieck et al. (2015) measurements, were used to validate the coupled model. The sensitivity of the monitor is 0.12 μg m^{-3} with a one second sampling time. Sampling tubes were run 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).

The real-time formaldehyde measurements were taken with the HRV operating for 40 minutes out of every hour at 205 m^3 h^{-1}, yielding an average hourly outdoor air ventilation rate of 137 m^3 h^{-1} (which corresponds to the ASHRAE 62.2-2010 minimum required ventilation rate for the house). In contrast, the HRV ran continuously at 171 m^3 h^{-1} during the measurement of formaldehyde concentrations used to calculate the emission rates in the coupled model. The simulated and measured concentrations are shown in Figure 3. The simulated and measured formaldehyde concentrations follow similar trends and are of the same magnitude in all of the zones. The average measured and simulated formaldehyde concentrations in the basement, first, and second floors was 7.9 μg m^{-3} (standard deviation=0.9 μg m^{-3}) and 8.3 μg m^{-3} (standard deviation=0.2 μg m^{-3}), respectively. The average measured and simulated formaldehyde concentrations in the attic were 22.2 μg m^{-3} (standard deviation=2.3 μg m^{-3}) and 19.5 μg m^{-3} (standard deviation=2.0 μg m^{-3}), respectively. With the coupled model validated with real-time formaldehyde measurements, different outdoor air ventilation rates were simulated to observe the effects on indoor concentrations and energy use.

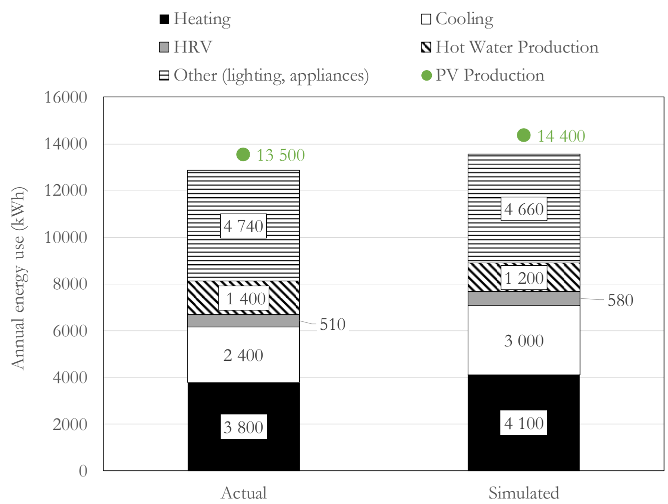

Figure 2 Comparison of actual and simulated annual energy use and PV production

Simulations

The following outdoor air ventilation rates were simulated: HRV off, 171 $m^3 h^{-1}$ (NZERTF ventilation rate), 137 $m^3 h^{-1}$ (ASHRAE Standard 62.2-2010 minimum requirement), 280 $m^3 h^{-1}$ (ASHRAE 62.2-2013 minimum requirement), and a rate to bring both formaldehyde and acetaldehyde below nondeleterious, noncancerous benchmarks (RfC and cREL values in Table 1). Simulations were performed using an AMY weather file for the KGAI weather station for July 2013 to July 2014 (Weather Analytics 2014). The modeled HRV fan power was increased in proportion to the increase in airflow rate from the NZERTF ventilation rate, but no other changes to the performance parameters were made. The IAQ and energy use consequences of the five outdoor air ventilation rates were compared.

RESULTS AND DISCUSSION

The simulated annual average formaldehyde and acetaldehyde concentrations, calculated for the 1st and 2nd floors, for the five outdoor air ventilation scenarios as a function of the total simulated energy use are shown in Figure 4. The acetaldehyde and formaldehyde health references are shown as horizontal red lines. The simulated annual energy use for net-zero operation (14 400 kWh) is shown as a dotted vertical green line.

Formaldehyde. Despite source control measures to minimize the use of building products with urea-formaldehyde resin, none of the simulated ventilation rates reduced concentrations below the concentration associated with a cancer risk of 1 in 1 000 000 (0.08 $\mu g\ m^{-3}$). The outside concentration of formaldehyde measured at the NZERTF was also above this concentration. The simulated NZERTF annual average formaldehyde concentration of 7.1 $\mu g\ m^{-3}$ was lower than the formaldehyde concentration associated with a cancer risk of 1 in 10 000 (8.0 $\mu g\ m^{-3}$) and the OEHHA cREL (9.0 $\mu g\ m^{-3}$). The simulated concentration was also 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). The average outdoor ventilation rate measured in the homes in the Hult study was 0.26 h^{-1}, which is equivalent to 330 $m^3 h^{-1}$ in the NZERTF and is almost twice the ventilation rate of the NZERTF. The average outdoor ventilation rate measured in the Offermann study was 0.24 h^{-1}, which is equivalent to 305 $m^3 h^{-1}$ in the NZERTF and a little more than 1.5 times more than the NZERTF ventilation rate. At a 25 % lower outdoor air ventilation rate, the ASHRAE 62.2-2010 rate of 137 $m^3 h^{-1}$, the simulated annual average concentration of formaldehyde increased 17 % to 8.5 $\mu g\ m^{-3}$. When accounting for the measured average outdoor formaldehyde concentration, the ASHRAE 62.2-2010 ventilation rate results in a concentration that is above both the 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}). The simulated annual energy savings would be 4 % when ventilating 25 % less using the KGAI AMY weather file.

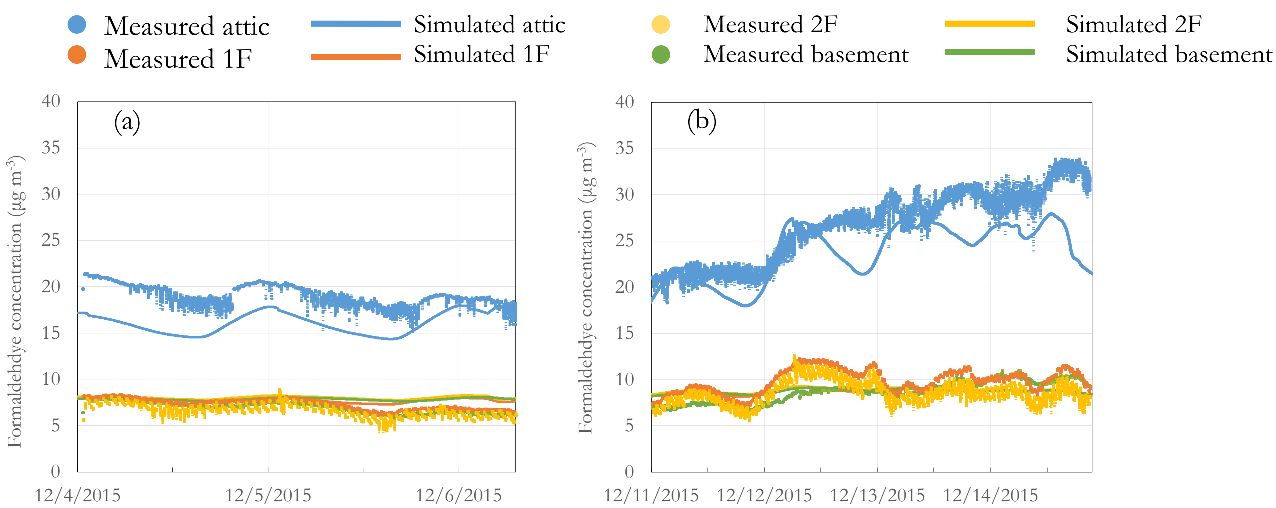

Figure 3 Real-time formaldehyde concentration data from two sampling sessions. (a) Average outdoor temperature was 3.5 °C (b) Average outdoor temperature was 12.7 °C. Average wind speed (both sessions) was 0.9 m s^{-1}

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 the concentration associated with a cancer risk of 1 in 1 000 000 (0.5 µg m^{-3}). At the NZERTF outdoor air ventilation rate, the simulated annual average acetaldehyde concentration was 15.7 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}). Roughly 35 % of the 108 California homes had acetaldehyde concentrations lower than the EPA RfC value (Offermann 2009). The outdoor air ventilation rate required to bring the levels of acetaldehyde concentrations below the EPA RfC would be at least the ASHRAE 62.2-2013 rate of 280 m^{3} h^{-1} with an associated energy increase of at least 13 % using the KGAI AMY weather file. At this ventilation rate, the model predicts the house would no longer achieve net-zero energy use for the year as operated, i.e. heating and cooling with an air-to-air heat pump and ventilating continuously. Without any mechanical outdoor air ventilation, the indoor concentrations of formaldehyde and acetaldehyde would be almost 85 % higher with an associated 20 % reduction in annual energy use.

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, unoccupied, and occupied only on occasion for maintenance or tours. Hence, the data presented in Figure 4 only accounts 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 own skin oils (Salthammer et al. 2010). Hence, contaminant modeling of building product emissions should only be used a starting point when designing or setting ventilation rates.

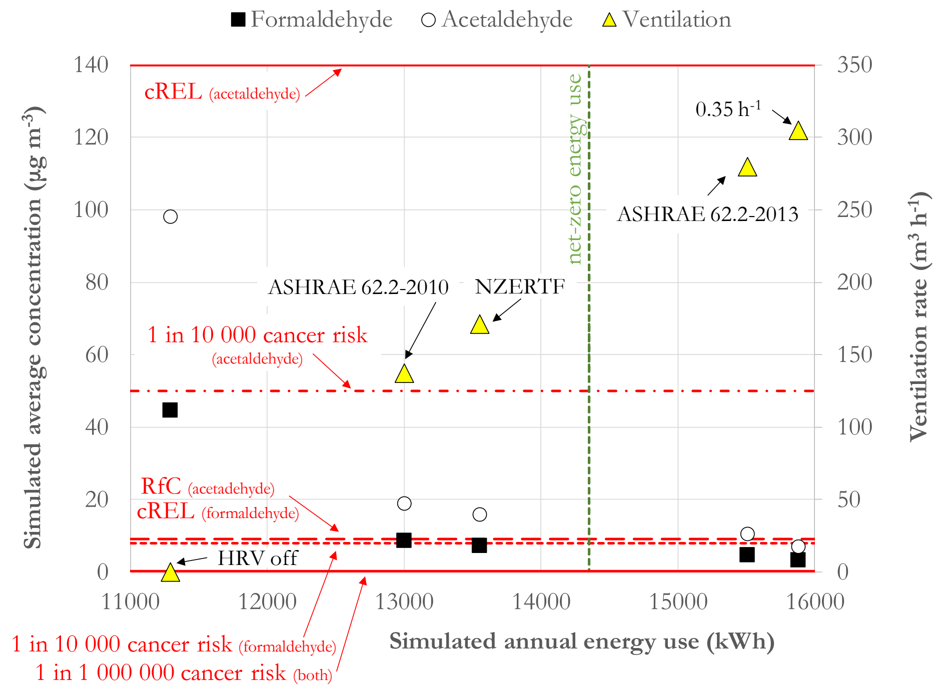

Figure 4 Simulated annual average formaldehyde and acetaldehyde concentrations for five ventilation rates and their associated simulated annual energy consumption

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 guidelines 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 were used to calculate emission rates that were input into a coupled CONTAM-EnergyPlus model of the house to verify that these design goals were met. The model was also used to study the effect of lower and higher 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. 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. The NZERTF could be operated at a 25 % lower ventilation rate (4 % energy savings) and still meet the OEHHA cREL of 9 µg m^{-3} for formaldehyde, which is a health benchmark below which there are deemed to be no deleterious noncancerous impacts. However, to prevent nondeleterious, noncarcinogenic effects from acetaldehyde exposure (EPA RfC of 9 µg m^{-3}), the building outdoor air ventilation rate would have to increase more than 39 %, with an associated annual energy increase of more than 13 %. At this rate, the NZERTF, as currently operated, would no longer achieve net-zero operation given the weather conditions of the year modeled. This study demonstrates that selecting appropriate 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 prevent deleterious, noncarcinogenic chronic effects, increased outdoor air ventilation rates may be needed but could come at the cost of net-zero energy operation. An IAQ design target of an acceptable cancer risk of 1 in 1 000 000 may be difficult to achieve for some chemicals, such as formaldehyde, with any reasonable ventilation rate, 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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