Balancing Energy and IAQ: NIST Net-Zero Energy Residential Test Facility

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Balancing Energy and IAQ: NIST Net-Zero Energy Residential Test Facility

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Buildings used 39 % of all energy used in the United States in 2017, with residential buildings and commercial buildings accounting for 20 % and 19 % (EIA 2018) respectively. Zero energy buildings have the potential to help extend and accelerate the recent trend where building energy use is actually decreasing over time. The U.S. Department of Energy provides the following definition of zero energy (or net-zero energy, NZE) buildings (DOE 2015):

> *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.*

For zero energy buildings, the amount of renewable energy generated equals or exceeds the energy used at the building site. However, we must not forget one of the reasons that buildings exist – to provide shelter and comfort to those that live and work within them-- so buildings should not adversely affect the health of their occupants.

Researchers within the Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) support this pursuit for more efficient buildings that compromise neither comfort nor health. A key “laboratory” used by the EL researchers is a residential test house called the Net-Zero Energy Residential Test Facility (NZERTF). This facility is an important tool for helping the development and adoption of cost-effective building energy technologies, design methods, and construction practices that aid the transition to zero energy homes, while also maintaining a healthy and comfortable indoor environment for the building occupants (Fanney et al. 2015).

Achieving the goals of reduced energy use and meeting occupant needs presents difficult challenges to those that design and construct buildings. The goal of this article is to introduce the NZERTF and to present some of the methods and measurements being utilized at this facility to investigate how to reduce energy use while maintaining indoor air quality (IAQ). For this study, IAQ is evaluated based on changes in occupant exposure to airborne contaminants. Occupant exposure is quantified using both direct measurement and whole-building simulation, and discussed in relation to building ventilation practices and contaminant source control.

The NZE Test House. The NZERTF is a laboratory test house. The design was meant to reflect the homes in the surrounding communities in both size and aesthetics. The NZERTF is located on the NIST campus in Gaithersburg, Maryland. It is a 252 m^2 (2,700 ft^2) two-story house with a basement and attic that are both 135 m^2 (1,450 ft^2). The total volume of the house is 1,270 m^3 (44,900 ft^3). The design team consisted of engineers and architects with broad expertise in building design, construction and thermal energy systems. Building components and construction techniques were implemented to establish a high performance building thermal envelope. This envelope minimizes both the heat and air transfer by taking advantage of advanced framing and insulation technologies that resulted in all the floors of the house, including the attic, being located within the conditioned space (Petit et al. 2014). Energy technologies implemented within the building include both high-efficiency space-conditioning systems, water heating systems, and renewable energy generation systems. In some cases, multiple, redundant systems were installed, but the base configuration implemented and addressed in this article include: a high efficiency air-to-air heat pump, a heat recovery ventilator (HRV), a 10.2 kW photovoltaic system, and a heat pump water heater with solar thermal preheat. Other systems that were not part of the baseline configuration include: geothermal heat pumps with three different ground loop configurations, a small-duct, high velocity heating and cooling system, a multi-split heat pump system, and a whole house dehumidifier. The 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 connect the attic to the second floor. The house is not occupied, but internal heat and moisture loads as well as energy and water usage of a virtual family of two adults and two children were emulated using automated heat generators, moisture sources, and water fixtures (Omar et al. 2013).

The goals of attaining net-zero energy were achieved by the baseline systems over a one year demonstration period under normal operating conditions, i.e., while maintaining the thermal setpoints and scheduled occupant loads. During this period, thermal comfort measurements were taken continuously and indoor and outdoor concentrations of formaldehyde and 30 other volatile organic compounds (VOCs) were measured approximately monthly to evaluate the occupant-related comfort and health parameters. Referenced publications, architectural drawings and specifications, and one year's of measurements can be found on the NIST NZERTF website (http://www.nist.gov/el/nzertf/).

Build tight, ventilate right. To support a high-quality indoor environment within the NZERTF, two fundamental principles were employed: "Build tight, ventilate right" and implement contaminant source control. The "build tight" goal for this house was an air leakage rate of less than 1.0 h^{-1} at 50 Pa based on fan pressurization testing (ASTM 2010). This goal was realized by using a continuous air barrier system (Figure 1) installed by well-trained laborers according to strict specifications and procedures. Blower-door tests were performed to confirm that the envelope airtightness not only met, but exceeded the design target. The measured building leakage rate is 0.63 h^{-1} at 50 Pa. This level of envelope leakage is tighter than the requirements in LEED v4 (USGBC 2014) and ENERGY STAR v3.1 (EPA 2015), and only slightly leakier than the Passive House U. S. requirement (PHIUS 2015). The normalized leakage value for the house equals 0.06, which is tighter than 99 % of U.S. homes based on statistical analysis of the Lawrence Berkeley National Laboratory Residential Diagnostics Database (Chan et al. 2013).

Figure 1. Left: continuous air barrier system. Right: NZERTF upon completion.

To “ventilate right”, a balanced and ducted HRV system supplies outdoor air to the home, while drawing air for heat recovery from the bathrooms. To comply with the minimum ventilation requirements of ASHRAE Standard 62.2-2010 (ASHRAE 2010), the HRV was sized to deliver at least 80 cfm (137 m^{3} h^{-1}) of outdoor air. The HRV was actually operated at a higher rate (100 cfm (171 m^{3} h^{-1})) due to the discreet fan speed settings of the unit.

Source control. Contaminant levels in a building can be mitigated using dilution by ventilation air, direct removal via exhaust air, or reducing or eliminating sources, i.e., source control. With respect to source control, the NZERTF minimizes the use of building products that contain urea-formaldehyde resin while incorporating building products that have low VOC emission rates. The guidelines for the building product selection and construction best practices for IAQ, as applied specifically at the NZERTF, are available as architectural specifications on the NIST NZERTF website (http://www.nist.gov/el/nzertf/).

Thermal comfort. An air-to-air heat pump system was used to provide space heating and cooling. The house was operated as a single zone with constant thermostat set points of 75°F (23.8°C) and 70°F (21.1°C) during the cooling and heating seasons, respectively. Dry bulb temperature, globe temperature, and relative humidity were continuously monitored in several rooms in the house (Figure 2) to verify that the heating and cooling system is providing a thermally acceptable environment throughout the NZERTF relative to the criteria provided by ASHRAE Standard 55-2017. These measurements will also be used to compare the thermal comfort delivered by different types of heating and cooling systems. However, these results were not available at the time of publication of this article.

Figure 2. Thermal comfort sensors.

Net-zero energy. A one-year demonstration period to verify whether or not the NZERTF could achieve the net-zero energy design goal began July 1, 2013. During this 12-month period from July 2013 through June 2014, the house exceeded the design goal by producing 484 kWh more electrical energy than it used (Figure 3).

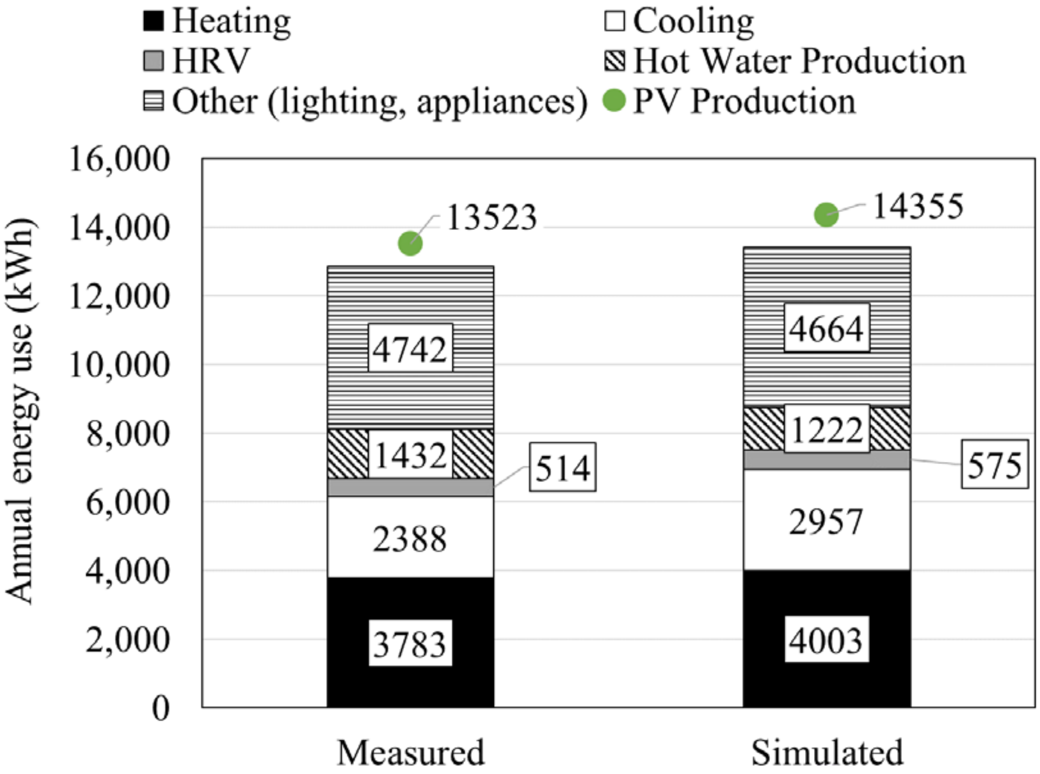

Figure 3. Measured vs. simulated electrical energy use for one year at NZERTF.

Source control works. Long term sampling and monitoring in this unfurnished house operated with simulated occupancy provided a unique opportunity to investigate sources of indoor VOCs attributed strictly to the building itself as opposed to furniture and other occupant-related sources. After construction of the home, indoor and outdoor concentrations of formaldehyde and 30 other VOCs were measured approximately monthly (Poppendieck et al. 2015). Measured whole-building averaged formaldehyde emission rates of the NZERTF were at least four times lower than comparable houses (Ullah et al. 2016). Despite exceeding some formaldehyde health benchmarks, the NZERTF formaldehyde concentrations were lower than those in comparable new houses. The NZERTF geometric mean formaldehyde concentration was lower than 13 occupied Indoor airPlus homes and was in the lowest 10 % of measured formaldehyde concentrations in 108 occupied, code-compliant homes (Ullah et al. 2016). These lower formaldehyde concentrations may be attributable to the NZERTF being unfurnished and/or unoccupied, both of which could contribute to reduced formaldehyde concentrations.

Ventilation matters. Mechanical ventilation is not free, but it is worth it. If no mechanical ventilation were provided, the concentrations of VOCs such as pentanal, hexanal, acetone, toluene, and d-Limonene would increase 6-fold to more than 8-fold (Poppendieck et al. 2015). Even though there is a penalty associated with the additional fan power required by the HRV, the cost of operating the HRV more than paid for itself with the heat pump energy savings when compared to ventilation being provided without heat recovery (Ng et al. 2016). The annual heat pump energy required to condition the outdoor air mechanically supplied by the HRV was 7 % less than the energy required if outdoor air were supplied without heat recovery.

Energy & IAQ. How much more mechanical ventilation could be provided while still achieving net-zero energy? What would the resulting formaldehyde concentrations be? We investigated these questions with a coupled thermal-airflow model of the NZERTF (Ng et al. 2017). The model was verified against measured energy use (Figure 3) and real-time formaldehyde concentration measurements. The verified model was then used to simulate the energy use and indoor concentrations of formaldehyde for different outdoor air ventilation rates.

Five levels of outdoor air ventilation rate were simulated as outlined in Table 1. The first level is HRV off (weather-driven infiltration only), two levels were based on ASHRAE Standard 62.2 requirements for the 2010 and 2016 versions of the standard, one was the measured ventilation rate, and the highest rate was selected to reduce formaldehyde below the California Office of Environmental Health Hazard Assessment (OEHHA) chronic relative exposure level (cREL) below which there are deemed to be no harmful noncancerous impacts (Table 2).

Table 1. Simulated Ventilation Rates

Ventilation Rate			**Description**
cfm	$m^3 h^{-1}$	h^{-1}	
0	0	0.00	HRV off (weather-driven infiltration only)
80	137	0.09	ASHRAE Standard 62.2-2010 minimum requirement
100	171	0.11	NZERTF measured ventilation rate
164	280	0.18	ASHRAE 62.2-2016 minimum requirement
308	525	0.35	Extreme mitigation level (also ICC 2009)

Table 2. Summary of Health References for Formaldehyde

Agency/Reference	**Type**	**Concentration limit (µg m^{-3})**
EPA (1989)	1 in 1 000 000 cancer risk	0.08
EPA (1989)	1 in 10 000 cancer risk	8.00
OEHHA (2016)	cREL	9.00

The energy use consequences and concentrations of formaldehyde resulting from the five outdoor air ventilation rates are shown in Figure 4. The figure shows the simulated annual average formaldehyde concentrations (black squares), averaged over the first and second floors, for the five outdoor air ventilation rates as a function of the total simulated energy use. The ventilation rates are plotted as triangles, which correspond to the values on the right axis. The formaldehyde health references are shown as horizontal red lines. The simulated photovoltaic production using Typical Meteorological Year 3 (TMY3) weather data at the NZERTF location (15,730 kWh) is shown as a dotted vertical green line. This line represents the net-zero energy crossover, where energy use lower than this value represents the case for achieving net-zero energy.

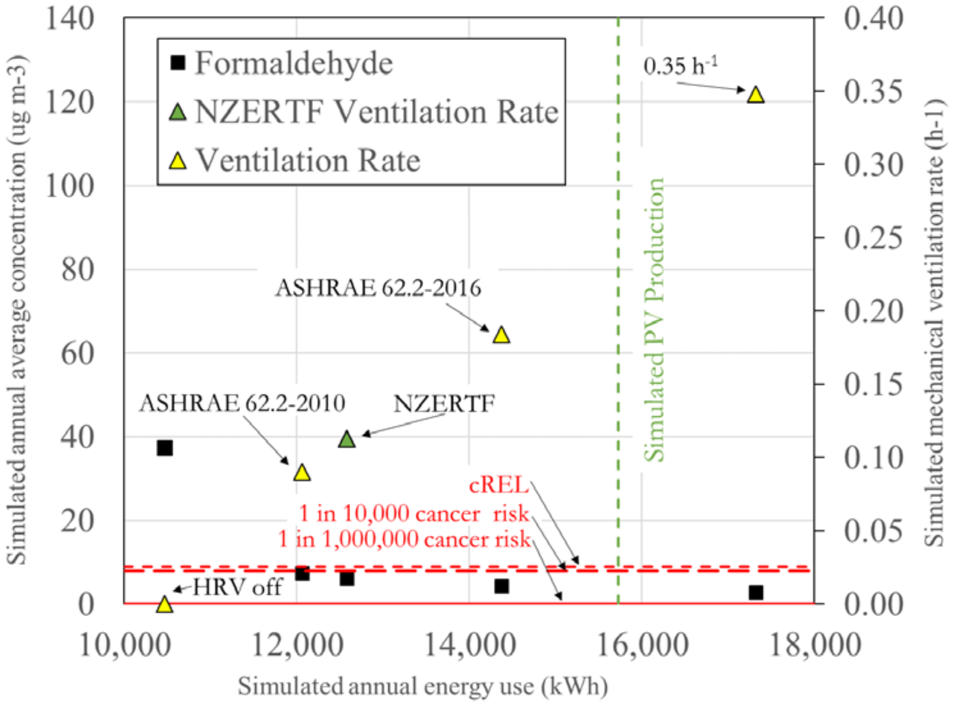

Figure 4. Simulated annual average formaldehyde concentrations for five ventilation rates and their associated simulated annual energy use

Not surprisingly, the higher mechanical ventilation rates resulted in lower predicted formaldehyde concentrations. 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 mainly because, like most locations in the United States (EPA 2017), the average outside concentration of formaldehyde measured at the NZERTF (0.80 µg m^{-3}) was above the risk level. All but the highest ventilation rate yielded simulated total energy use below the simulated annual energy production value, i.e., the net-zero energy break-even point. According to these results, the ventilation rate could be increased to reduce the average formaldehyde levels below the 1 in 10,000 cancer risk level (but not below the 1 in 1,000,000 cancer risk level), while still achieving the net-zero energy goal.

Table 3 shows the 90th percentile and maximum concentrations over a simulated year for the 1st and 2nd floors combined and the attic for the five ventilation rates. The maximum simulated formaldehyde concentration in the attic could reach approximately 120 µg m^{-3} when the HRV is operating, 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 cREL (9.0 µg m^{-3}). For the simulated HRV-off case, the concentrations were as high as 150 µg m^{-3} in the attic and 100 µg m^{-3} in the combined first and second floor. 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) were all around 120 µg m^{-3}, which implies that increasing the ventilation in the occupiable areas did not impact the concentrations in the passively ventilated spaces.

Table 3. Comparison of simulated formaldehyde concentrations for 5 mechanical ventilation rates

	HRV off (0.00 h^{-1})	**62.2-2010 (0.09 h^{-1})**	**NZERTF (0.11 h^{-1})**	**62.2-2016 (0.18 h^{-1})**	**IMC-2009 0.35 h^{-1}**
	1st and 2nd Floor Combined				
90th percentile (µg m^{-3})	71	11	9	6	4
Maximum (µg m^{-3})	100	16	14	11	7
	Attic				
90th percentile (µg m^{-3})	100	81	80	78	78
Maximum (µg m^{-3})	150	120	120	120	120

Conclusion. The NIST NZERTF demonstrated that net-zero could be achieved in a home of similar size and aesthetics to those in the surrounding community for the base configuration of the facility. The measurements at the NZERTF provided valuable input to computer simulations that can help improve our understanding of the relationship between building energy use and IAQ. The results show that some VOC concentration health benchmarks are achievable in a net-zero energy residential building simply through careful selection of building materials. However, not all health benchmarks that were addressed are currently achievable in this facility. These benchmarks are likely to require new, innovative approaches to building design and operation and vigorous VOC requirements. This is especially true in relatively airtight homes and when other sources of VOCs are introduced by furniture and occupant-related contributions that were not present in the NZERTF. Further, mechanical ventilation is necessary even if it consumes additional energy because some VOC concentrations will increase many-fold without it. For more information and a list of all publications related to the NZERTF, please visit http://www.nist.gov/el/nzertf/.

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