NIST's Net-Zero Energy Residential Test Facility in Gaithersburg, Md., is used to test energy-efficient concepts in a home with conventional architecture. NIST

TESTING GROUND FOR NET ZERO

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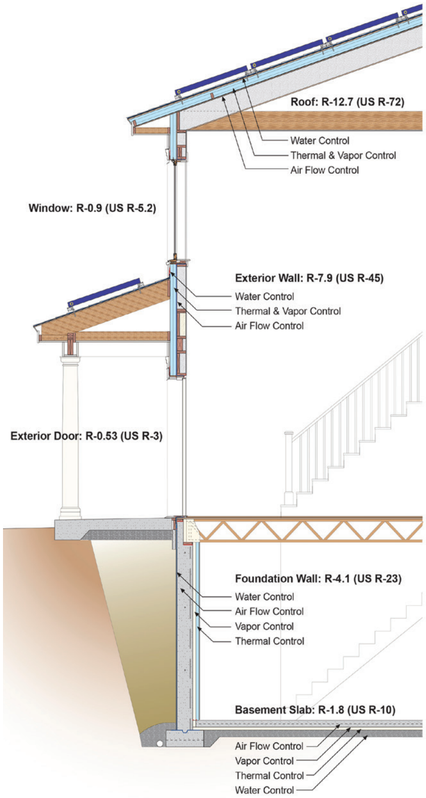
IN 2012 THE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY (NIST) completed the construction of a Net-Zero Energy Residential Test Facility (NZERTF) to demonstrate that it is possible to achieve net zero for a newly constructed house with conventional architecture, amenities, and size compared to homes in the surrounding area. Equally important, the facility serves as a testbed to evaluate residential renewable and energy-efficient technologies and various approaches to improving indoor air quality. Since completion, the NZERTF has been operated as an all-electric home connected to the electric grid. Natural gas is available at the facility to enable the future testing of gas-fired residential equipment.

Built on NIST's Gaithersburg, Md., campus, this LEED Platinum home incorporates a vast array of renewable and energy-efficient technologies. Unique features include three independent ground source heat exchangers, a radiant floor heating system in the basement, a solar hot water system with variable solar collector area and storage capacity, a 10.2 kW photovoltaic system, and a ducted heat recovery ventilation system. The facility also incorporates three different means of providing conditioned air throughout the house—a sealed sheet metal air distribution system; a high-velocity air distribution system; and provisions to incorporate a multi-head mini split heat pump system. A subset of these systems, described below, were used during the first year of operation.

Overall Design/ Building Envelope

The house faces true south and has two stories of living area 2713 ft^2 and a fully conditioned basement 1453 ft^2. The first floor includes the kitchen and dining area, a family room, an office (optional bedroom), a full bathroom, an open foyer to the second floor, and a utility closet. The second floor consists of a master bedroom



Details of the construction technique and materials used in various components of the NZERTF's building envelope.

Detailed drawings and specifications may be found at www.nist.gov/el/nzertf/

Continuous moisture/air barrier being applied to the exterior of building envelope. Note green extension boxes on window/door apertures necessary to accommodate the 4 in. of foam insulation that will be applied to the exterior walls.

Overhang structures applied over sealed building envelope. Two layers of 2 in. thick foil-faced polyisocyanurate foam insulation board being installed. Fenestration openings sealed with foam board for a blower door test prior to window and door installation. Five blower door tests were conducted at various stages of construction.

with adjoining bathroom, two additional bedrooms, a second bath, and a hallway. The finished basement contains the majority of the facility's mechanical/electrical equipment, whereas the detached garage contains the data acquisition/control equipment associated with the facility.

The exterior above-grade walls are insulated using a combination of blown cellulose between the studs and two layers of 2 in. foil-faced polyisocyanurate exterior to the plywood sheathing. The interior of the basement walls is insulated with extruded polystyrene board adhered to the inside of the concrete walls with a foil-faced polyisocyanurate insulation board applied over the extruded insulation. Insulation of the roof assembly consists of 5 in. foil-faced polyisocyanurate insulation applied in three layers sandwiched between two layers of plywood sheathing. The cavity between roof rafters was filled with blown in cellulose insulation. The interior of the roof assembly was finished using gypsum board with taped joints. Double-hung windows incorporate two panes of low-e coated glass with a suspended film positioned between them. The cavities between the glass panes and the suspended film are filled with an inert gas. The NZERTF's building envelope was constructed using a continuous air barrier system to minimize infiltration. Blower door tests have yielded an average air exchange rate of approximately 0.6 air changes per hour at 50 Pa.

Renewables

The NZERTF uses renewable energy through the use of photovoltaic and solar hot water systems. The 10.2 kW photovoltaic system, with a nominal 19.6% conversion efficiency, is mounted on the main roof of the house. Two 5 kW-rated inverters, having a measured weighted efficiency of 95.5%, are used to convert the direct current into 60 Hz alternating current. The solar hot water system uses two single-glazed flat-plate thermal collectors and an 80 gallon storage tank. The hot water leaving the solar storage tank enters a thermostatic mixing valve before entering a downstream heat pump water heater (HPWH). Both the photovoltaic and solar water heating collectors are facing true south at a tilt angle of 18.4 degrees.

Heating, Ventilation and Air-Conditioning

The space heating and cooling system is a 2 ton air-to-air heat pump system incorporating a two-speed scroll compressor and variable-speed indoor fan. A conventional sheet-metal air distribution and return duct system, contained within the conditioned space, is used to distribute air throughout the

Solar hot water storage tank (grey tank) and heat pump water heater (white tank). Also shown is the PEX hot and cold "home run" water distribution manifold and lines. The home run system was used in conjunction with electric solenoid valves and a data acquisition system to automate water usage.

BUILDING AT A GLANCE

Name Net Zero Energy Residential Test Facility

Location Gaithersburg, Md.

Miles from nearest major city 20 Miles NW of Washington, D.C.

Owner NIST

Principal Use Research/Demonstration
Employees/Occupants Four Virtual Occupants

Expected (Design) Occupancy Four Virtual Occupants

Percent Occupied 100%

Gross Square Footage 4,165

Conditioned Space 4,165

Distinctions/Awards
USGBC LEED Platinum, EPA Energy Star, DoC Energy and Environmental Stewardship Award, Wintergreen Award for Excellence

New Construction

Total Cost $656,399 (Estimate/No Lot/No Site Work or Permit Fees)

Cost per Square Foot $158 (Estimate/No Lot/No Site Work or Permit Fees)

Substantial Completion/Occupancy July 2012

ENERGY AT A GLANCE (U.S)

Annual Energy Use Intensity (EUI) (Site) 10.68
Electricity (Grid Purchase) 0.00
Electricity (on-Site Solar or Wind Installation) 10.68

Annual On-Site Renewable Energy Exported 0.4

Annual Net Energy Use Intensity –0.4 kBtu/ft^2

Annual Source (Primary) Energy –1.26 kbtu/ft^2

Annual Load Factor 0%

Savings vs. Standard 90.1-2007 Design Building N/A—Residential

ENERGY STAR Rating Yes

Carbon Footprint 0

Percentage of Power Represented by Renewable Energy Certificates 0
Number of Years Contracted to Purchase RECs N/A—Federal Installation

Percentage of Carbon Deferred by Purchasing Offsets 0
Number of Years Contracted to Purchase Offsets N/A—Federal Installation

Heating Degree Days (Base 65˚F) 5,159

Cooling Degree Days (Base 65˚F) 1,367

Annual Hours Occupied 8,760

WATER AT A GLANCE

Annual Water Use 30,550 gallons

KEY SUSTAINABLE FEATURES

Water Conservation Low Flow Showers/Faucets/Toilets/Vertical Plumbing Stack/Home Run Manifold Plumbing System

Recycled Materials Counter Tops

Daylighting Not Used

Individual Controls Not Used

Carbon Reduction Strategies Photovoltaic and DHW Solar Systems, High Efficiency Equipment, Airtight Construction, Building Envelope R-Values > 2X Local Energy Code

Transportation Mitigation Strategies Close Proximity to County Bus Station, Shuttle Bus, and Washington, D.C. Subway System

Other Major Sustainable Features Rainwater Capture System, Use of Low Emission Materials, Mechanical Ventilation to Meet ASHRAE Standard 62.2-2010

BUILDING ENVELOPE

Roof
Type Wood Frame
Overall R-value R-72
Reflectivity 0.3

Walls
Type Wood Frame
Overall R-value R-45
Glazing Percentage 13.66%

Basement/Foundation
Slab Edge Insulation R-value R-10
Basement Wall Insulation R-value R-23
Basement Floor R-value R-0.5
Under-Slab Insulation R-value R-10

Windows
Effective U-factor for Assembly USI=1.1356 (U=0.20)
Solar Heat Gain Coefficient (SHGC) 0.25
Visual Transmittance 0.4

Location
Latitude 39.14 North
Orientation South

BUILDING TEAM

Building Owner/Representative
National Institute of Standards and Technology

Architect Building Science Corporation

General Contractor
Therrien Waddell Construction Group

Mechanical Engineer EBL Engineers

Electrical Engineer EBL Engineers

Energy Modeler
NIST/Building Science Corporation

Structural Engineer Jay Crandell

Civil Engineer CTI Consultants

Lighting Design Building Science Corporation

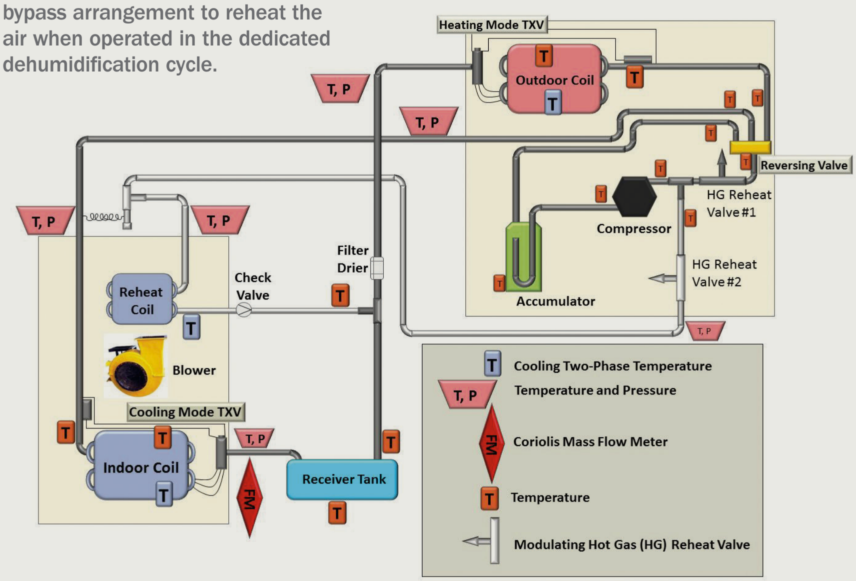
LEED Consultant Everyday Green

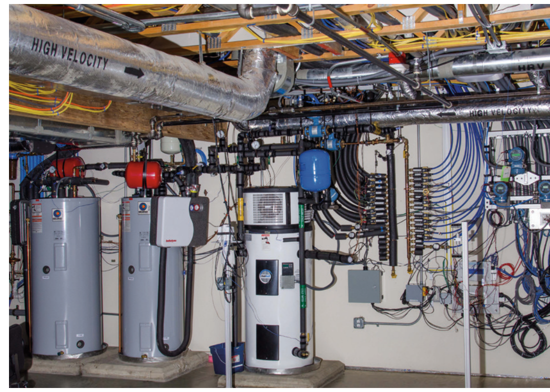
Commissioning Agent NIST

house. All duct joints were sealed with tape and mastic and each individual duct run was pressure tested to ensure minimal air leakage. Dehumidification is provided by using the heat pump's unique dedicated dehumidification cycle, available in the cooling mode only. This cycle reduces the indoor unit's fan speed to enhance the indoor coil's ability to remove moisture while using a hot gas bypass arrangement in conjunction with a reheat heat exchanger. A supply air temperature sensor provides the control signal used to proportionally modulate the flow of hot refrigerant gas through the reheat heat exchanger to maintain a preset supply temperature during dedicated dehumidification.

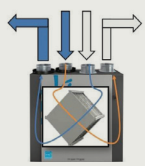
Outdoor ventilation air is supplied to the NZERTF via a balanced supply and exhaust system driven by a heat recovery ventilator (HRV) with a rated effectiveness of 0.78. The duct system associated with the HRV supplies outdoor air to all bedrooms and the kitchen, and exhausts air from the three bathrooms. The unit was sized to provide a total of 81 cfm of outdoor air in accordance with requirements in ASHRAE Standard 62.2-2010. Given the discrete settings on the HRV's fans, however, the ventilation

The heat pump incorporates a hot gas bypass arrangement to reheat the air when operated in the dedicated dehumidification cycle.





Basement of NZERTF showing ductwork, water distribution system, solar hot water storage tanks, heat pump water heater, and associated instrumentation.



A heat recovery ventilator is used to condition outdoor ventilation air prior to it being introduced into the NZERTF. The HRV exchanges thermal energy between the entering and exiting ventilation air.

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rate was 25% greater than required at approximately 101 cfm. The house has additional local exhaust air systems comprised of a kitchen exhaust fan and a dryer exhaust. The kitchen exhaust fan is activated whenever the cooktop is energized, and the exhaust rate was measured to be 104 cfm.

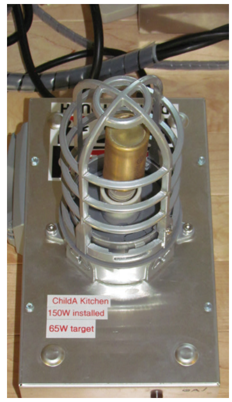
Emulating Occupancy

The NZERTF incorporates a virtual family of four to realistically emulate the daily activities of an actual family. Appliance, water, and plug load user profiles, developed by DoE's Building America Program, were used for emulating occupancy in the NZERTF. All appliances and plug loads are automated according to a schedule such that over the course of a year the devices consume the same quantity of energy as they would in a typical four-member family. Some plug loads involve real devices; others, which are difficult to automate, are emulated with resistive loads. Occupancy, appliance, plug loads, and lighting schedules vary daily, with the greatest occupancy-driven energy consumption occurring during the weekends. Each lighting fixture is controlled to coincide with the movement of the virtual family members. The appliance, plug, lighting, cooking, and occupant load profiles are described in great detail in "Simulating Occupancy in the NIST Net-Zero Energy Residential Test Facility" (http://tinyurl.com/zzch6aq).

The emulation of human occupancy accounts for the sensible and latent loads generated by the presence and activities of the occupants themselves. In the NZERTF, sensible loads generated by the occupants are simulated by resistive heaters placed in the various rooms. Latent loads, resulting from the occupants and cooking activities, are introduced as water vapor through the use of modified ultrasonic humidifiers. The sensible and latent load emulators are activated according to the occupancy schedules. The energy used to run the devices that emulate human occupancy is provided by a separate electrical system within the house that is not part of the metered energy consumption of the house.

Test Conditions

During the year-long experiment the thermostat's setpoints were fixed at 70°F (21°C) for heating and 75°F for cooling (24°C) with automatic changeover. In the cooling mode the humidistat is set such that the dehumidification mode of the heat pump is activated if the relative humidity reaches 50%. The weekly schedule



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Modified ultrasonic humidifiers (left) are used to replicate the moisture that would be introduced into the NZERTF by an actual family of four. Electric resistance heaters placed throughout the home (right) are used to supply the sensible heat of the four occupants. Both are computer controlled in accordance with the occupancy schedule of the house. Energy used by these devices is not charged to the electrical energy consumption of the house.

was repeated for the entire 52-week test interval. Snow and ice that accumulated on the solar collectors for 38 days during the year was not cleared by human intervention, but rather by the weather-induced melting.

Energy Performance

Figure 1 shows the measured daily and cumulative net electricity use for the first year of operation. A positive value indicates that the house produced more energy than it consumed and represents the quantity of energy exported to the grid. A negative value indicates that the house imported energy from the grid to meet the energy usage over the 24-hour period. For the 12 months (July 2013 through June 2014), excluding five days of missing data in August, the house produced 484 kWh more electrical energy than it consumed.

The house consumed 13,039 kWh of energy during the one-year test interval. The top five energy end uses for the 12-month interval were space heating, plug loads, space cooling, appliances, and heat pump water heater. The appliances with the greatest energy consumption were the clothes dryer (542 kWh) and the refrigerator (410 kWh). Plug loads were included for devices that are found in 50% or greater of American homes. The plug loads with the greatest annual energy consumption were television sets, cable boxes, a wireless router, personal computers, and cell phone chargers.

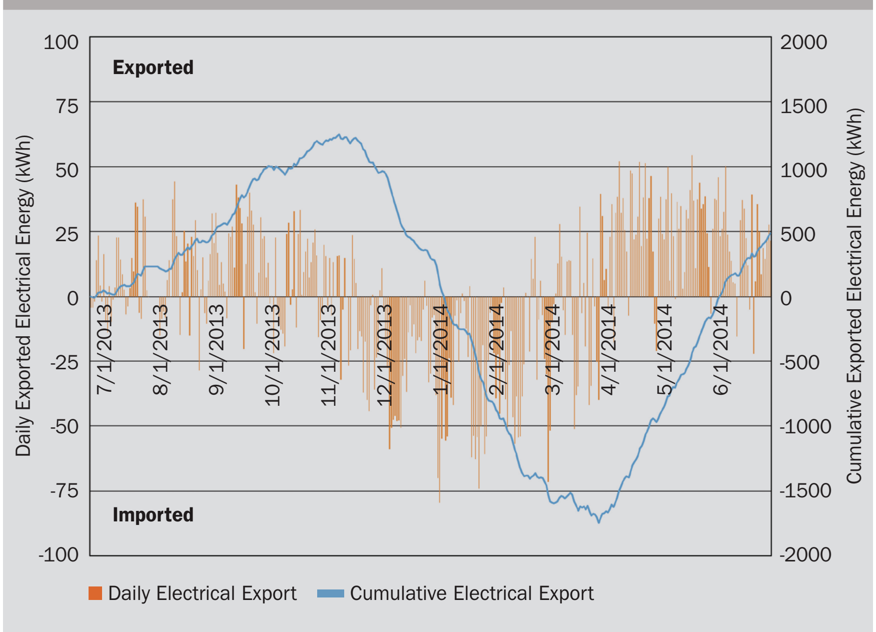
The solar photovoltaic system converted 16.8% of the incident solar irradiance into AC electrical energy. Fifty-four percent of the energy required to meet the domestic hot water load over the 12-month interval was provided by the solar hot water system. These overall conversion efficiencies include the 38 days that the photovoltaic array and solar thermal collectors were partially or totally covered by snow or ice. The circulating pumps associated with the solar water heating system consumed 320 kWh during the year. Of the total energy consumed by the heat pump water heater unit, 975 kWh (88%) was consumed by the heat pump and controls and 137 kWh (12%) by the auxiliary resistive heating element.

When operated in the cooling mode, the heat pump operated with a seasonal COP (total thermal load/total electricity consumed) of 3.19 compared to the rated value of 3.82. In the heating mode, the measured seasonal COP was 2.06 compared to the rated seasonal COP value of 2.65.

There are three primary reasons that the measured seasonal COP values were less than the rated seasonal COP

Figure 1

DAILY EXPORTED/IMPORTED ELECTRICAL ENERGY

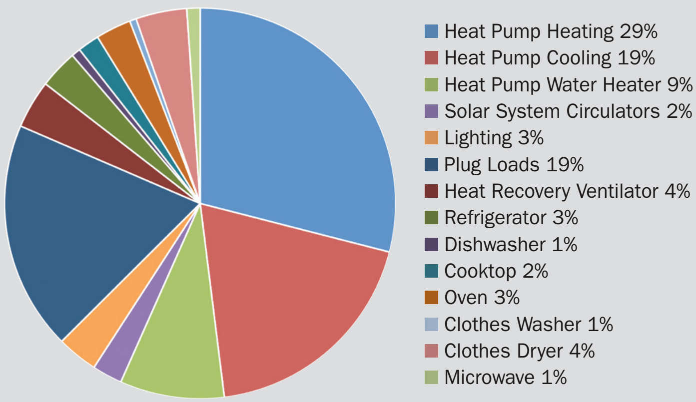


The daily energy imported and exported by the NZERTF during the first year of operation.

Figure 2

NZERTF ENERGY END USES, JULY 2013–JUNE 2014
PERCENT OF TOTAL ENERGY CONSUMPTION (13039 KWH)

Breakdown of total energy consumed by NZERTF into Various End Uses.



values. Standby energy is not taken into account in the rating procedure used to determine rated seasonal performance. Also, the current rating procedure does not address the degradation in performance when this unique heat pump unit operated in a dedicated dehumidification mode during a portion of the cooling season to maintain a 50% relative humidity. Finally, the rating procedure used to determine seasonal heating efficiency does not include the impact of resistive heat during the defrost cycle or when auxiliary resistive heat is required.

During the seven months that cooling was required, the sensible to total load ratio varied from 0.58 to 0.78. Currently, most high-efficiency heat pump systems operate with a sensible to total load ratio of greater than 80%. The higher latent loads associated with low energy homes will benefit from new technologies and control strategies that better address moisture removal.

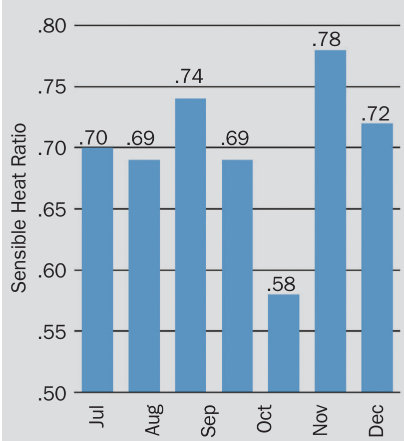
An analysis was performed to quantify the energy usage associated with the heat pump operation due to additional thermal loads introduced by the HRV. The HRV has two energy impacts: the fan energy and the increase or decrease in the thermal load resulting from introducing outdoor air into the house.

For example, when the outdoor air temperature is lower than the indoor air temperature, additional energy will be required to heat the home during the heating season compared to an identical home without an outdoor air ventilation system.

During the cooling season, the introduction of outdoor air may increase or decrease the sensible and latent loads, depending on the outdoor air temperature and moisture content relative to the indoor temperature and relative humidity. During the one-year period, the HRV consumed a total of 514 kWh in fan energy. The annual energy required to ventilate the house using the HRV is the total of the additional energy to run the heat pump, 1451 kWh, to meet the additional thermal load introduced by the HRV, plus 514 KWh of HRV fan energy, for a total of 1965 kWh.

Figure 3

MEASURED SENSIBLE TO TOTAL
LOAD RATIO—COOLING MONTHS



Measured sensible to total heat load ratio for cooling months. Residential heat pumps have traditionally been designed for a 0.80 sensible heat ratio.

Materials and Indoor Environment

To support indoor environmental design goals in the NZERTF, both source control and pollutant removal techniques (i.e., mechanical outdoor air ventilation and particle filtration) were undertaken. To control indoor contaminant sources, guidelines for the selection of products used inside of the airflow control layer (or air barrier membrane) were developed. The intent of these guidelines was to identify and use products with relatively low emissions of volatile organic compounds (VOCs) that are toxic, cause sensory irritation, and/or have low odor thresholds. Particular emphasis was placed on reducing known sources of formaldehyde emissions such as composite woods containing conventional resins. VOCs emitted from wet-applied materials and acetic acid, an odorant and suspected chemical irritant found in numerous interior products, also were targeted.

The impacts of the efforts to limit airborne concentrations of formaldehyde and other VOCs in the facility control were investigated through an IAQ monitoring study conducted over the course of a year. It was found that

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Sampling pumps for periodic VOC and formaldehyde measurements made in living room, second floor hallway, and outside.

the measures taken to reduce the use of medium density fiberboard and particleboard in the cabinetry and other finished products were effective for controlling indoor formaldehyde concentrations.

Based on the lessons learned in their application to the NZERTF, the guidelines for low-emitting interior sources have been updated and formalized into architectural specification language. Bernheim + Dean, Inc. (with specification assistance by White + GreenSpec) and Berkeley Analytical have developed a detailed architectural Division 01 specification, "Section 01 81 13.01, Sustainability Requirements—Indoor Air Quality" intended specifically for residential new construction and major renovations. This specification differs substantially from the original guidelines and emphasizes a more performance-based approach than the guidelines. This change is made possible by the existence today of considerably more product data on VOC emissions that has been generated by manufacturers interested in demonstrating compliance of their products to LEED low-emitting materials credits and the requirements of other high-performance building standards and codes. The specification itself is available at www.nist.gov/el/nzertf/.

Despite efforts to minimize the thermal stratification with the NZERTF, the average temperature of the second-story rooms tended to be warmer than the rooms on the first floor throughout the year. The difference tended to be greater during the summer. The run times of the heat pump and associated indoor blower unit tend to be significantly less in low energy and net zero energy buildings relative to a conventional home resulting in less mixing of the air volume within the home. Thus, in low-energy homes, it may prove beneficial to operate ceiling fans or continuously operate the blower units in order to

Figure 4

DIFFERENCE BETWEEN INDOOR AND OUTDOOR MEASURED CONCENTRATIONS OF VARIOUS VOCS

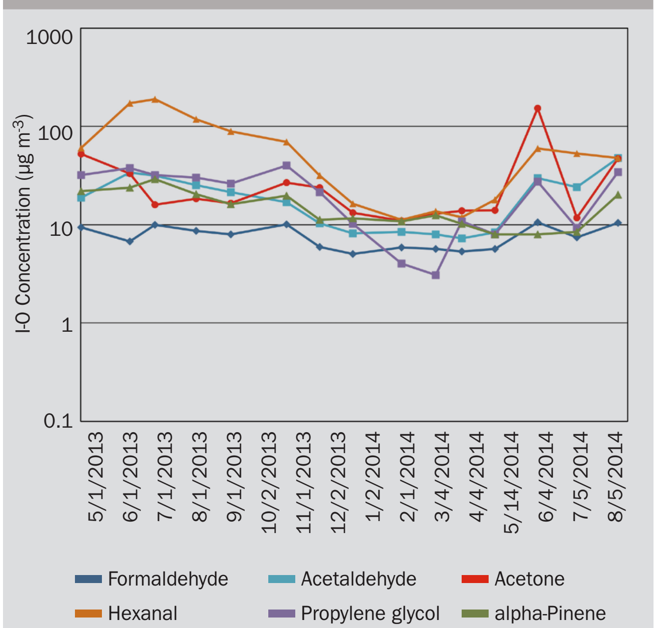
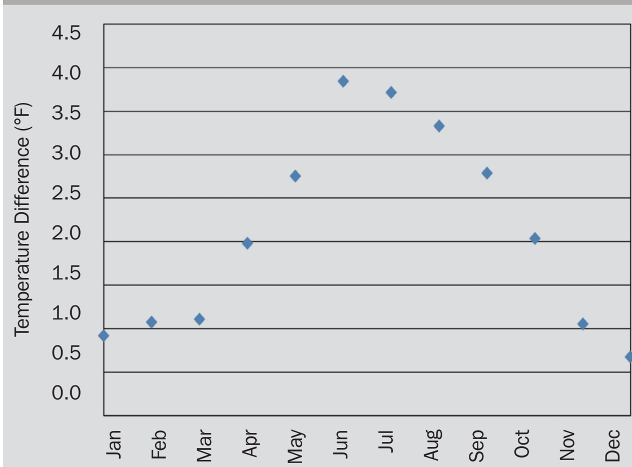


Figure 5

AVERAGE TEMPERATURE DIFFERENCE BETWEEN SECOND AND FIRST FLOOR



Temperature Difference Between the Second and First Floors Tended to be Greater During the Summer Months.

reduce the floor-to-floor stratification. However, both strategies will consume additional energy.

Conclusions

The NZERTF serves both as a project to demonstrate that net zero can be achieved for a newly built home similar to those in the surrounding communities and to serve as a testbed for building energy efficient and renewable technologies. During its first year of operation, the house generated a surplus of electrical energy. As a result of its well-designed building envelope and use of energy-efficient technologies, the NZERTF has an annual energy use intensity of 10.7 kBtu/ft^2 (33.8 kWh/m^2) or approximately 25.1% of the average EUI of single-family detached homes within the climate zone that the NZERTF is located.

The Home Energy Rating System is a measure of a home's energy efficiency. A typical new home has a score of 100 whereas a score of zero denotes a net zero energy home. The NZERTF has a Home Energy Rating System (HERS) score of 31 not considering photovoltaic system and an overall score of –6 when the photovoltaic system is included. Based on the lessons learned during the first year of operation, changes were made to the controls that operate the heat pump unit and the heat recovery ventilator. As a result of these changes and milder weather conditions, preliminary data analysis of the second year data show a significant increase in the excess energy that was supplied to the electrical grid.

The NZERTF is currently being reconfigured to compare the performance and thermal comfort of the air-to-air heat pump system used during the first two years of operation to a high-velocity heat pump system that uses the small duct air distribution system. The operation of the two heat pumps will be automated such that each one operates for a selected number of days, alternately back and forth between the two with automated dampers isolating the unit not being used. Extensive instrumentation has been installed to capture air velocity, temperature, humidity, and noise levels associated with these two space conditioning systems. The heat pump water heater's impact on the space conditioning load will also be quantified and alternative water heating options will be explored. ●

Lessons Learned

- Although the use of renewables is needed to achieve net zero, a well-designed and executed building envelope and the use of energy efficient building energy technologies can, by themselves, reduce the energy consumption of a new home significantly. In this particular case study, the energy use intensity of this home is 75% less than an identical home built to comply with the local energy code.
- Net zero can be achieved for a new house with conventional architecture, full amenities, and typical size through the use of a well-designed and executed building envelope, efficient building energy technologies, and appropriately sized solar systems.
- A photovoltaic system, using central inverters, is significantly impacted by snow cover when any module is partially or fully covered by snow and/or ice. Significant periods of time are required for snow/ice cover to melt on the solar photovoltaic system, as a result of the well-insulated roof assembly keeping heat loss to a minimum.
- Actual performance of a heat pump system will be less than that projected using laboratory test procedures. Rated performance does not fully capture a number of factors including standby energy, resistive heat during defrost cycles, controls that are not optimum, and, in the case of this particular heat pump, the degraded performance that occurs when the heat pump operates in its dedicated dehumidification cycle.
- The sensible to total heat load capacity ratio of future residential heat pumps will need to be lower to provide adequate moisture control in low energy/net zero energy homes.
- Through the use of careful material selection, formaldehyde levels within the unoccupied/unfurnished NZERTF were lower than those commonly found in occupied furnished homes.
- Mechanical ventilation consumes energy, but it is crucial to providing acceptable indoor air quality.

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Snow/ice conditions were present for 38 days during the test period.

ABOUT THE AUTHOR

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