Lessons Learned from a Year at the NIST Net-Zero Energy Residential Test Facility

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In 2012, the National Institute of Standards and Technology (NIST) in Gaithersburg, MD completed construction of the Net-Zero Energy Residential Test Facility (NZERTF), a research laboratory intended to measure the performance of building systems used in efficient homes (Figure 1). This "laboratory," however, is not your typical research facility. Instead, it was designed and built as a typical single family home that could readily blend into the suburbs of Washington, DC, albeit while incorporating some of the most efficient building practices and equipment commercially available at the time.

NIST, which is an agency of the U.S. Department of Commerce, aims to promote innovation and industrial competitiveness in the United States by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life. To that end, the NZERTF was constructed to explore how to best measure and report performance of systems and equipment in low energy/net-zero energy buildings and to collect accurate data to help the building industry improve the energy efficiency and indoor environment of homes.

The home, designed by Building Science Corporation under contract from the U.S. Department of Energy's Building America program and built by Therrien Waddell Construction Group, has 252 m^2 (2700 ft^2) of living space on the first and second floors as well as a 135 m^2 (1500 ft^2) unfinished basement that is within the conditioned space[i]. This size represents the average size of new homes built in the United States at the time. A detached garage, with a separate electrical system, contains all data acquisition equipment, thereby moving both the associated heat and electrical loads that would not normally be present in a home into the garage. While no people live in the house, a virtual family of four is emulated in the house on a minute-by-minute basis to represent occupants' activities as well as the associated heat and moisture generation. The NZERTF was designed to have features and amenities of a typical home, in part to show visitors that one does not need to sacrifice expected comforts and functions to live in an energy efficient home. The facility is supplied by both electric and gas service, but the initial phase of operation considers the house in an all-electric mode.

Building Enclosure

As with any high performance home, the design process started with a well-insulated and air-tight enclosure. Walls were built using advanced framing concepts, with 2x6 studs spaced 610 mm (24 inches) on center and a continuous layer of 19 mm (¾ inch) plywood sheathing covering the stud walls. Wall cavities were filled with blown-in cellulose insulation, and a peel-and-stick housewrap was affixed to the exterior of the sheathing. This moisture and air barrier extends from the concrete foundation wall to the peak of the roof, putting the entire interior (including the attic) within conditioned space. Exterior of the housewrap, there are two additional layers of 51 mm (2 inch) polyisocyanurate board insulation, yielding an overall R-value of 7.9 m^2K/W (45 $ft^2 \cdot h \cdot °F/Btu$) for the walls (Figure 2).

The roof is constructed in a similar manner, with 2x12 roof rafters filled with cellulose insulation spaced 610 mm (24 inches) on center and three layers of polyisocyanurate insulation on the exterior yielding an R-value of 12.7 m^2K/W (72 $ft^2 \cdot h \cdot °F/Btu$). Double glazed windows with a suspended film positioned between the two panes of glass are installed throughout the building; each window has a rated R-value of 0.9 m^2K/W (5 $ft^2 \cdot h \cdot °F/Btu$). The basement walls, which are largely below grade on all sides, are insulated on the interior side with a 51 mm (2 inch) layer of polyisocyanurate board laid on top of a 51 mm (2 inch) layer of extruded polystyrene board to yield an R-value of 4.1 m^2K/W (23 $ft^2 \cdot h \cdot °F/Btu$). Beneath the 102 mm (4 inch) concrete slab, a 51 mm (2 inch) layer of extruded polystyrene rigid foam slab insulation provides an R-Value of 1.8 m^2K/W (10 $ft^2 \cdot h \cdot °F/Btu$).

The continuous air barrier system combined with rigorous sealing of penetrations resulted in an air change rate of 0.6 air changes per hour at 50 Pa as measured with a fan pressurization test. For this level of airtightness, mechanical ventilation is required. The NZERTF uses a dedicated balanced system with a heat recovery ventilator that is sized and operated to meet ASHRAE Standard 62.2-2010 ventilation rate requirements.

Heating, Cooling, and Water Heating Equipment

The team at NIST envisioned testing several types of heating and cooling systems in future research efforts, so the NZERTF was constructed with an air-source heat pump, three different geothermal loops, and refrigerant lines to accommodate a variable refrigerant flow multi-split system. Conventional sheet metal ducting was installed as well as ducting that would be used with a future small-duct, high-velocity system.

In the first year of operation, the team used the air-source heat pump (Figure 3). Given the expectation that latent loads would be much greater relative to typical sensible loads, a unit was selected that had a built-in dedicated dehumidification cycle. A separate dehumidifier was also installed in the house but was not necessary in the first year with the heat pump's dedicated cycle. Given the expected small load, the unit has a rated cooling capacity of 7.6 kW (2.2 tons) and a rated heating capacity of 7.8 kW (26.6 kBtu/h).

Water heating is provided by a two-tank solar thermal system (Figure 4). The first tank is a 303 L (80 gallon) storage tank for water heated by the solar panels. Water from this tank feeds into the backup unit, a 189 L (50 gallon) heat pump water heater. Valves are installed to bypass either of these systems or to use a separate 454 L (120 gallon) solar storage tank, but the two tank configuration was used during the first year with the expectation that it would be the most efficient option. Water is delivered to end uses by a "home-run" system through cross-linked polyethylene tubing.

Lighting and Appliances

The facility is equipped with all appliances that would be expected in a modern home, including clothes washer, electric clothes dryer, dishwasher, refrigerator, and cooking appliances. A review of U.S. Census data identified devices present in at least 50 % of American households; those devices were either placed in the house or emulated using resistors having the same energy consumption as a typical device. All lighting in the house uses either fluorescent or light-emitting diode technology.

Renewable energy

The facility has a 10.2 kW photovoltaic array installed on its south facing roof that is pitched at an 18.4° tilt. The 32 modules have a rated efficiency of 19.6 %, making them some of the most efficient commercially available panels on the market at the time of installation. The array is split into 4 strings. Two inverters are located in the attic of the house, each accepting the input from two of the strings. No battery storage is in place in the house, with excess energy fed directly back to the grid.

Sensors

As a research testbed, the facility is set up with over 700 channels of potential data flows. In the first year, approximately 400 data points were collected. Each circuit is instrumented to provide power, current, and power factors. Dry bulb temperature sensors in each room along with relative humidity and radiant temperature sensors in a select set of rooms are used to assess whether thermal comfort requirements are being met (Figure 5). Detailed measurements of hot water flow and temperatures are used to assess the efficiency of the hot water system, and weather sensors provide air temperatures, wind speed and direction, and solar insolation. Instrumentation in the heat pump provides capacity data, efficiency data, and sensible and latent loads.

Results

Prior to using the facility as a full-fledged research testbed, the team conducted a one-year test to assess whether the facility would actually meet the net-zero energy goal. A simulated weekly occupancy pattern based on Building America benchmarks for a typical family was implemented, with lighting, appliances, and hot water usage occurring in the home as would be expected. Initial computer simulations estimated that the PV array would generate a surplus of approximately 15 % of the energy consumed in the home…but reality always seems to throw curve balls!

The one-year test was conducted from July 1, 2013 through June 30, 2014. Figure 6 shows the daily electrical energy exported to the grid along with the cumulative electrical export from the start of the test to the end. While the goal of reaching net-zero seemed like a distant hope towards the end of the winter, springtime PV production and milder temperatures resulted in a surplus of 484 kWh generated compared to an overall energy consumption of 13 039 kWh[ii]. This 4 % surplus in generated energy was less than expected, but these results led to great lessons learned, even though they may not be totally surprising. But, as we drive down the energy consumption of homes, such small details begin to matter. Some of these lessons include:

Lesson 1) 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 home significantly. In this particular case study, the energy use intensity of the home is 75 % less than an identical home built to comply with the local energy code.

Lesson 2) No matter how efficient a heating and cooling system, a bad thermostat can ruin the best of plans. In this house, it was decided to maintain fixed temperature setpoints of 24 °C (75 °F) in the cooling season and 21 °C (70 °F) in the heating season. While the heat pump capacity was sufficient to maintain these setpoints, the thermostat control engaged resistance heating after a fixed amount of time if the temperature remained below the set point, but still within the thermostat's dead band. This mode of operation ended up consuming much more energy than the heat pump would have consumed to meet the heating load without such frequent use of resistance heating.

Lesson 3) Actual performance of equipment will often be less than that projected using laboratory test procedures. For example, the rated performance of the heat pump 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.

Lesson 4) PV doesn't work very well with snow cover. This observation is obvious, but the region experienced an unusually large amount of snowfall during the test year. To make matters worse, the highly insulated roof minimized the amount of heat rising from the house to melt the panels. The relatively low pitch of the roof also hindered the rate at which snow was cleared by wind and gravity. For

38 days, the solar panels were totally or partially covered by snow. And, with PV connected to central inverters, partial coverage of the array means that the output from the entire system is essentially zero.

Lesson 5) Ventilation's impact on heat pump energy is significant, but the indoor environment needs it. The HVAC systems of the house (including the heat pump and the heat recovery ventilator fans) consumed 6684 kWh over the year, accounting for approximately 50 % of the overall energy consumption. Of this amount, 513 kWh were required to continuously operate the HRV fan. Detailed measurements and analysis showed that 13 % of the heating and cooling energy consumption was used to condition outdoor air supplied by the HRV[iii]. The use of heat recovery, however, yielded a 7 % savings in heat pump energy use compared to a simulated case where no heat recovery was in place, showing the value of a controlled ventilation scheme. While it would be easy to suggest a decrease in ventilation air, a companion study measured contaminant levels of 15 VOC's under different ventilation rates as well as indoor temperatures[iv]. This work observed significant increases in contaminant levels when the ventilation system was turned off. It is clear that the implications of ventilation are complicated and that results are very dependent upon climate, but the balance between energy consumption and contaminant levels for this particular case study will be explored further in a future EDU article.

Despite these lessons learned, the well-designed house met the goal of net-zero with some room to spare. A subsequent year-long test, during which the heat pump thermostat control and the HRV ventilation rates were adjusted, resulted in a much larger surplus of energy, admittedly part of which resulted from more favorable weather. Preliminary analysis shows a yearly energy surplus of 2139 kWh of electricity, with a total of 11 578 kWh of energy consumed during the second year.

NIST is preparing to release all data for use by researchers in the field. It is hoped that the data will be useful in developing validated simulation modeling procedures, data management and analysis schemes, and observations of performance of many other efficient homes.

In future issues of EDU, detailed looks at particular aspects of the NZERTF's performance will be discussed. One article will look at the performance of the equipment in the home, a second will cover the indoor environmental quality measurements, and a third article will focus on computer modeling and economics.

Figure 1: NIST Net-Zero Energy Residential Test Facility

Figure 2: Exterior insulation and roof overhangs being applied over house wrap.

Figure 3. Instrumented Air-to-Air Heat Pump Interior Unit with Dedicated Dehumidification Cycle.

Figure 4: Two-tank solar and heat pump water heater system with distribution manifold system. Second solar storage tank on left is reserved for future studies.

Figure 5: Thermal comfort sensors and simulated loads in a bedroom.

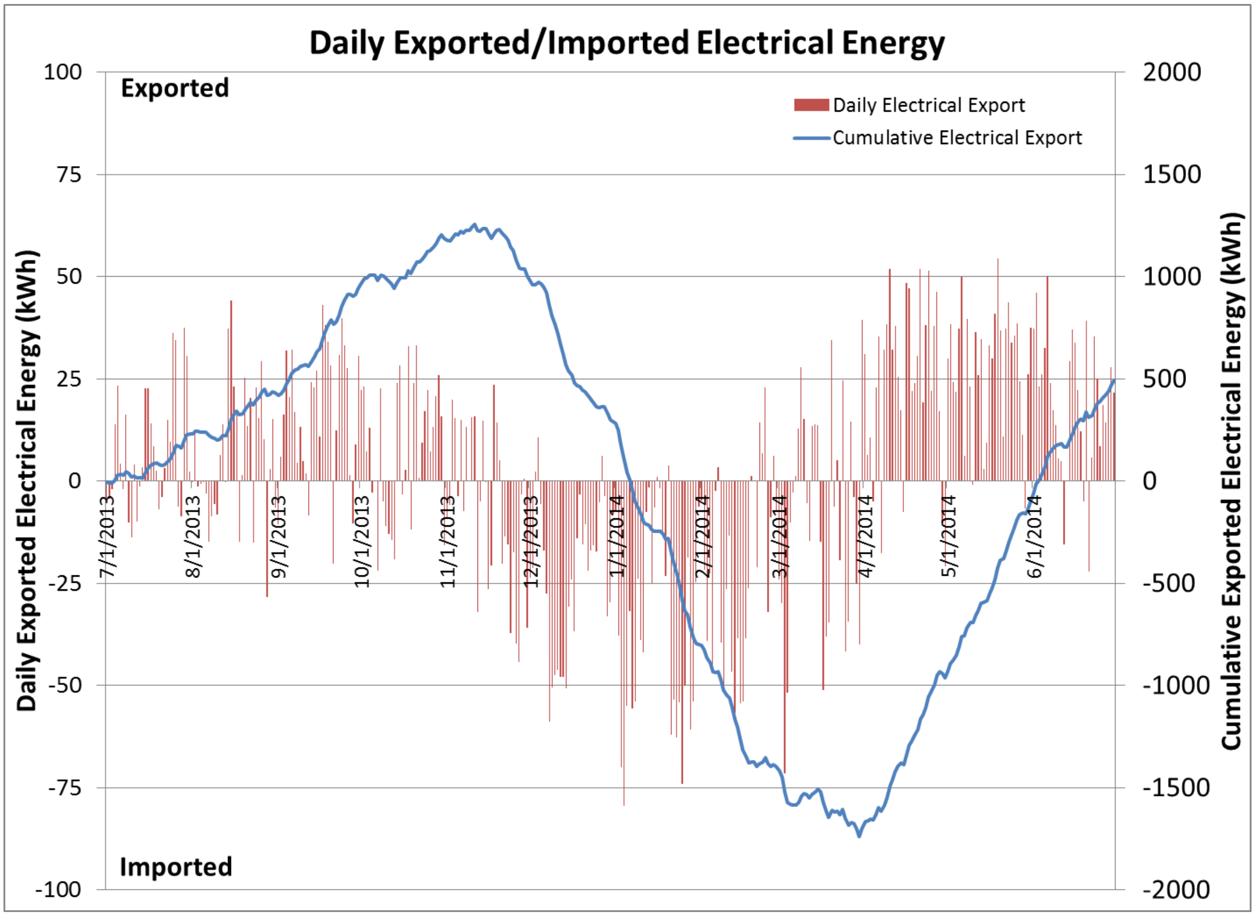

Figure 6: Daily electrical energy exported to grid along with running total of energy exported to grid over the first year of testing.

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[i] Pettit et al., “Design Challenges of the NIST Net Zero Energy Residential Test Facility”, NIST Technical Note 1847, March 2015.

[ii] Fanney et al., “Net-Zero and beyond! Design and Performance of NIST’s Net-Zero Energy Residential Test Facility” Energy and Buildings 101, 2015.

[iii] Ng and Payne, “Energy Use Consequences of Ventilating a Net-Zero Energy House” Applied Thermal Engineering 96, March 2016.

[iv] Poppendieck et al., “Long Term Air Quality Monitoring in a Net-Zero Energy Residence Designed with Low Emitting Interior Products” Proc. 13th Intl Conf on Indoor Air Quality and Climate, July 2014.