The NIST Net-Zero Energy Residential Test Facility – Equipment Performance

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The National Institute of Standards and Technology in Gaithersburg, MD has been conducting experiments in its Net-Zero Energy Residential Test Facility (NZERTF) to obtain performance data on a range of operational aspects of efficient single family homes. A previous article in EDU[1] discussed the overall lessons learned from a full year of testing and data collection with simulated occupancy of a four-person family. This article explores some of the key findings for the major pieces of equipment in the home over the course of the year; further details can be found in Fanney et al.[2].

Figure 1. Net-Zero Energy Residential Test Facility.

Heating and Cooling System

System Overview

The home has a total conditioned living area of 252 m² (2700 ft²) with an additional 135 m² (1500 ft²) unfinished basement that is within the conditioned space. The highly insulated and airtight enclosure results in heating and cooling loads that are less than those for a typical home of this size. Using the 1 % and 99 % design conditions along with ACCA Manual J, the sensible plus latent cooling load was estimated to be 4720 W (16 100 Btu/h), and the heating load was estimated as 5670 W (19 300 Btu/h). To meet the heating load, a 7.0 kW (24 000 Btu/h = 2 ton), two-speed split-system heat pump was installed. The part-load performance of the two-speed system provides a means for meeting more of the space heating season load while not compromising the overall latent removal during cooling. The

[1] Healy, "Lessons Learned from a Year at the NIST Net-Zero Energy Residential Test Facility."
[2] Fanney et al., "Net-Zero and beyond! Design and Performance of NIST's Net-Zero Energy Residential Test Facility."

two-speed heat pump operates at 75 % capacity under low-speed, or 5.3 kW (1.2 tons), and has a rated Seasonal Energy Efficiency Ratio (SEER) of 15.8 and a Heating Seasonal Performance Factor (HSPF) of 9.05.

A primary and necessary feature of the selected heat pump is a dedicated dehumidification operating mode. To enable this operating mode, the heat pump includes an extra, indoor heat exchanger and a modulating hot-gas reheat mechanism. Dedicated dehumidification is provided by operating the compressor and directing a controlled amount of the hot discharge gas to the indoor heating coil where the cooled and dehumidified air leaving the indoor evaporator is reheated to the room neutral temperature. Dedicated dehumidification is critical for the house in this mixed-humid climate, considering the extremely low sensible cooling loads resulting from the highly insulated envelope.

All distribution ductwork is installed in conditioned space, with a design airflow of 2039 m^3/h (1200 cfm). Ductwork was carefully sealed with mastic, yielding an approximate duct leakage of 251 m^3/h (148 cfm) at 25 Pa.

Temperature setpoints were maintained at 21 °C (70 °F) during the heating season and 24 °C (75 °F) during the cooling season, with the relative humidity setpoint being 50 %. No supplemental humidification is included in the facility.

Results

Over the first year of operation, the heat pump used 3783 kWh in heating mode and 2388 kWh in cooling mode, making the combined space conditioning load equal to 47 % of overall annual electrical consumption of the house (Figure 2). In both cooling mode and heating mode, the unit performed below its rated value. In cooling mode, the unit operated with a seasonal COP of 3.19 compared to the rated value of 3.82. There are two primary reasons for this discrepancy. First, standby energy consumption, which is not taken into account in the rating procedure, was 5.2 % of the total heat pump energy consumed. Second, the dedicated dehumidification mode results in a COP significantly less than when the heat pump operates in its normal cooling mode. As an example, in August 2013, the unit operated in dedicated dehumidification mode approximately 41 % of the time, and the measured COP during these times was 0.89. The current rating methodology does not consider dedicated dehumidification modes, so degradation in overall COP is not captured.

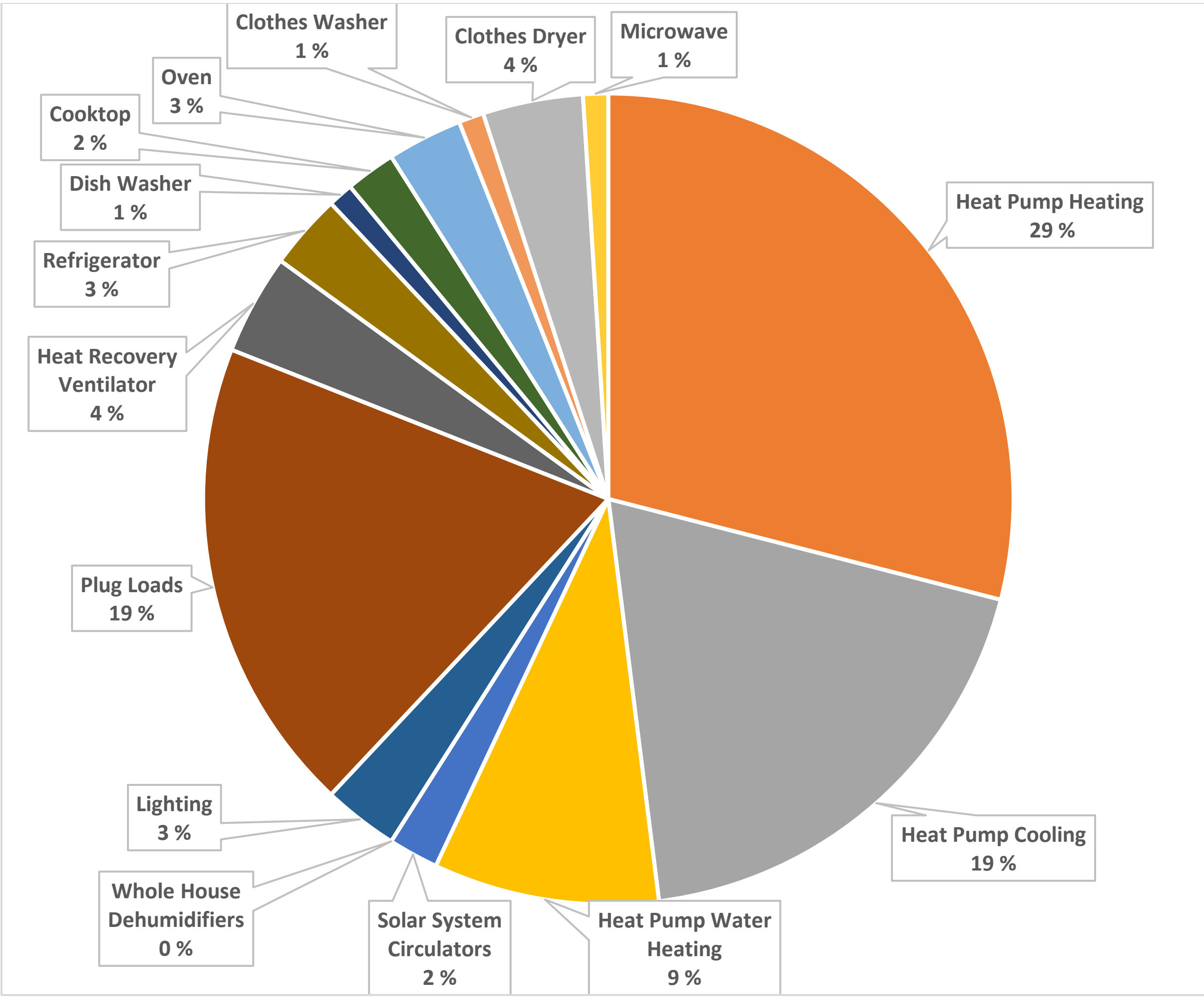

Figure 2. Breakdown of annual energy use in NZERTF.

The use of a heat pump with a dedicated dehumidification mode was justified by the measured sensible to total load ratio ranging between 0.58 and 0.78 for the cooling months. With most high efficiency heat pump systems currently operating with a sensible to total load ratio greater than 80 %, it is clear that the efficient envelope in this climate zone coupled with the typical internal moisture sources in this house required supplemental dehumidification. This moisture load partly arose because of the use of a dedicated ventilation system, which will be the focus of a future article.

In the heating mode, the measured seasonal COP was 2.06 compared to the rated seasonal COP value of 2.65. Standby energy has a small part in this discrepancy, amounting to 3.5 % of the energy consumption. The more significant reason for the discrepancy was the use of resistive heat. First, resistive heat is used when defrosting the outdoor unit, and this energy use is not included in the rating methodology. Additionally, the control algorithm used by the wall thermostat called for backup resistance heat more often than was necessary. The thermostat would engage resistance heat if the compressor operated continuously at high speed for 40 minutes without considering how much the temperature sensed by the thermostat lagged below the setpoint. As a result, rather than behaving similarly to typical thermostats that enable resistance heating only when the room temperature drops an extra degree or two below the activation temperature for heat pump heating, the programmable thermostat used during the first year demonstration instead increased energy use by the heat pump. As an example, in January 2014, 44 % of the electrical energy used for space heating was attributed to resistance heating; in Year 2, with the average outdoor temperature being within 2 °C of that in Year 1, resistance heating (used only for defrost) accounted for 8 % of electrical energy for space heating over the entire year.

During a second year of operation, a whole house dehumidifier was used in place of the heat pump's dedicated mode. Additionally, a different wall thermostat was installed that more appropriately regulated the use of resistance heat. The control logic of this alternative thermostat resulted in no resistance heat being used to supplement the heat pump heating to maintain the desired level of thermal comfort in the home. The use of a whole-house dehumidifier, however, did not improve energy performance, as the heat from the evaporator was expelled into the conditioned space instead of being rejected outdoors via the primary condenser of the central heat pump when operating in its dedicated dehumidification mode.

To more fairly compare the impact of the operational changes made between the first and second year-long demonstration periods, the effects of weather and different ventilation rates must be accounted for. The comparison was conducted by creating an EnergyPlus model of the house. The resulting simulations estimated that the combination of the better heat pump thermostat and use of a whole house dehumidifier (both done in Year 2) would have decreased the annual energy consumption for space conditioning from Year 1 to Year 2 by 524 kWh, an 8.5 % reduction.

Water Heating

System Overview

The domestic hot water system is a solar thermal system with a heat pump water heater as a backup. Two solar collectors, piped in parallel and having a total footprint of 4.4 m^2, are installed on the front porch roof. A two tank configuration, in which a 303 L (80 gallon) tank provides solar-preheated water to a 189 L (50 gallon) heat pump water heater, was implemented to provide flexibility for testing various configurations but was also estimated to be the most efficient commercially available alternative. Water draws from sinks, showers, and other devices were implemented to mimic the usage of the family.

Results

Over the course of the year, the water heating system consumed 1432 kWh, 11 % of the energy consumed by the house. Of that total water heating energy consumption, 78 % was used by the heat pump water heater (including its auxiliary resistance element) and 22 % by the pumps on the solar thermal system. The solar fraction was determined to be 0.54, and the solar energy factor (SEF), defined as the thermal energy delivered from the water heating system divided by the total energy consumption, was 2.39. An important issue with heat pump water heaters is the cooling effect on the space. Given the unit's rated Coefficient of Performance, it is estimated that the heat pump water heater added a cooling load of approximately 1600 kWh to the space over the twelve months of operation. During the year, the system experienced two major problems. For approximately 10 days, the pumps of the solar thermal system were not operational on account of a failure with an electrical connection. During a different 10 day period, the compressor of the heat pump water heater was not operational due to a control wire that had become disconnected, forcing the unit to operate exclusively in resistance mode.

The energy performance results raise a question as to whether this configuration is the most efficient, given that the solar energy factor is comparable to efficiency ratings of heat pump water heaters available on the market. A modeling study examined the energy use of various configurations over the course of a year[3]. The study examined the configuration implemented as well as ones with only a heat pump water heater, an electric resistance water heater, solar with electric resistance backup, and solar with an electric tankless water heater as backup. Figure 3 shows the estimated COP_{sys}, defined as thermal energy out of the system divided by total energy consumption, for these five configurations. The configuration with solar plus a heat pump water heater has the highest efficiencies throughout the year. While the overall annual SEF approached a typical Energy Factor of a heat pump water heater, the modeling of the heat pump water heater showed that the use pattern resulted in field performance lower than would be predicted from a typical rating. The predicted efficiencies for the solar configurations drop in the winter months due to less sunlight. An interesting finding, however, was that the heat pump water heater, when used as a backup to the solar preheat, operated significantly more in the winter than in the summer. This result means that an extra load was placed on the heating system in winter, but little cooling benefit occurred in the summer months[4]. To examine this effect, the modeling study also considered the impact on the space conditioning energy consumption, and, despite this behavior, the two tank configuration with a heat pump water heater is still estimated as being the most energy efficient option in this setting, even when taking into account the impact on space conditioning. It is acknowledged that the two-tank configuration with a heat pump water heater is expensive and may not currently make sense on a life-cycle cost basis. The configuration does, however, provide a prediction for a best-in-class technology.

[3] Balke, Healy, and Ullah, "An Assessment of Efficient Water Heating Options for an All-Electric Single Family Residence in a Mixed-Humid Climate."
[4] Ullah and Healy, "The Performance of an Auxiliary Heat Pump Water Heater Installed in a Dual-Tank System in a Net-Zero Energy Residence."

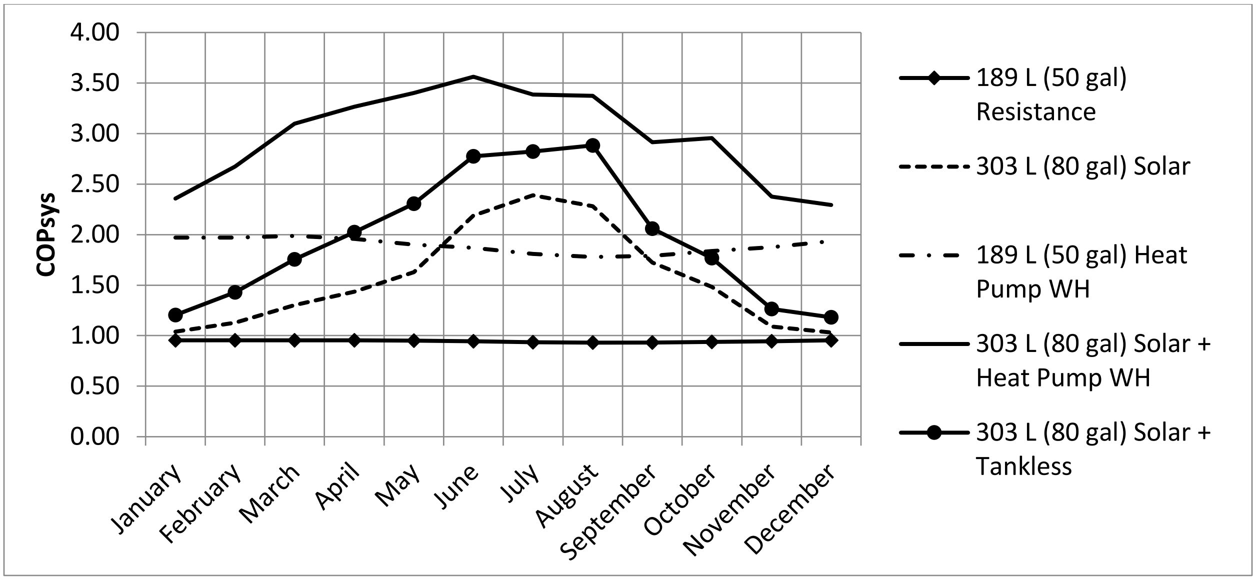

Figure 3. Modeled monthly efficiencies (COPsys = thermal energy delivered / electricity consumption) for five configurations. The configuration installed at the NZERTF is the 303 L (80 gallon) Solar Water Heater + Heat Pump Water Heater, which is modeled as having the highest efficiency during all months of the year.

Photovoltaics

System Overview

To achieve the goal of net-zero, a 10.24 kW (rated) photovoltaic system was installed that fills up nearly the entire south facing side of the main roof, as shown in Figure 1. The modules selected were some of the most efficient available at the time of construction; the rated efficiency of each 320 W module is 19.6 %. The modules are grouped into four series-wired strings, with two strings feeding separate inverters that convert the solar array's DC output into AC power. The two identical inverters, which yielded a measured weighted conversion efficiency of 95.5 %, are located in the attic of the house and are grid connected. No on-site battery storage is used. A weather station located adjacent to the array provides the solar insolation, wind, and temperature readings necessary for evaluating the system performance.

Results

The photovoltaic system has and continues to operate without issue. During the 1st year of demonstration, the annual conversion efficiency from sunlight to AC electrical energy was 16.8 %. One of the big factors affecting this efficiency was the large amount of snow cover that occurred; at least partial coverage of the array was observed for 38 days during the especially harsh winter. Many of those days were sunny, but even partial coverage of the arrays severely limits their output, as noted in Figure 4. On the particular day shown in this figure, the clear sky suggests the DC power output from the array would follow the upper plot based on the PVWatts computer model. The slight snow cover on the left side of the array, however, negates the output from three of the four strings (each row is connected as a single string), thereby yielding approximately a quarter of the expected output as shown in the lower plot. The monthly inverter efficiencies all exceeded 94.5 %. Overall, the system produced

13 523 kWh of AC electrical energy, exceeding the amount consumed by the house to achieve net-zero operation over the course of the year.

This discussion has focused on equipment performance, particularly the energy consumption/generation of three key systems. Of course, a low energy home is worthless if it does not maintain a comfortable and healthy indoor environment. To address these issues, a future article will dive more deeply into measurements of the indoor environmental quality and the performance of the ventilation system.

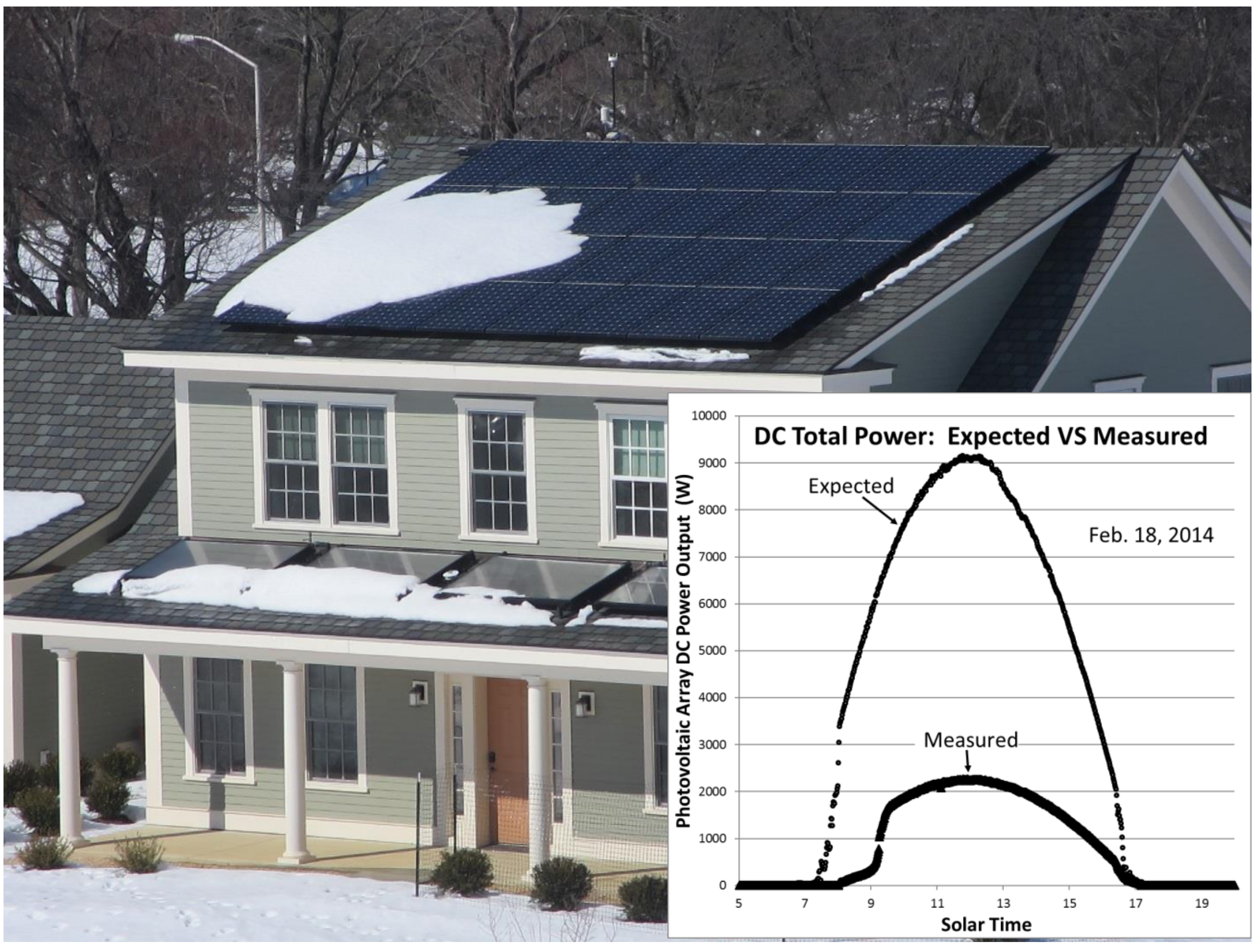

Figure 4. Effect of partial snow coverage of photovoltaic array on its electrical output.