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Small Changes Yield Large Results at NIST's Net-Zero Energy Residential Test Facility

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Abstract

The Net-Zero Energy Residential Test Facility (NZERTF) was designed to be approximately 60 % more energy efficient than homes meeting the 2012 International Energy Conservation Code (IECC) requirements. The thermal envelope minimizes heat loss/gain through the use of advanced framing and enhanced insulation. A continuous air/moisture barrier resulted in an air exchange rate of 0.6 air changes per hour at 50 Pa. The home incorporates a vast array of extensively monitored renewable and energy efficient technologies including an air-to-air heat pump system with a dedicated dehumidification cycle; a ducted heat-recovery ventilation system; a whole house dehumidifier; a photovoltaic system; and a solar domestic hot water system. During its first year of operation the NZERTF produced an energy surplus of 1023 kWh.

Based on observations during the first year, changes were made to determine if further improvements in energy performance could be obtained. The changes consisted of installing a thermostat that incorporated control logic to minimize the use of auxiliary heat, using a whole house dehumidifier in lieu of the heat pump's dedicated dehumidification cycle, and reducing the ventilation rate to a value that met but did not exceed code requirements. During the second year of operation the NZERTF produced an energy surplus of 2241 kWh. This paper describes the facility, compares the performance data for the two years, and quantifies the energy impact of the weather conditions and operational changes.

1. Introduction

In 2012 NIST completed the construction of a Net-Zero Energy Residential Test Facility (NZERTF) on its campus in Gaithersburg, MD to demonstrate that it was possible to achieve net-zero for a house with conventional architecture, amenities, and size comparable to those being constructed in the surrounding area, Fig. 1. The home was constructed to exceed all energy related aspects of the 2012 International Energy Conservation Code. Fanney et. al [1] give a detailed accounting of the overall performance of the house as well as the individual systems within the home for the first year of operation, July 2013 to June 2014. The economics of the NZERTF have been studied in detail by Kneifel [2] and Kneifel and O'Rear [3]. Indoor air quality within the NZERTF has been reported by Poppendieck et. al [4]. The energy impact of ventilating using a heat recovery ventilator and simple mechanical ventilation have been quantified by Ng and Payne [5]. Sustainability performance of the NZERTF has been compared to other code-compliant designs [6]. The NZERTF's energy

use and indoor air quality have recently been benchmarked to a variety of residential homes in the United States [7] using the Department of Energy's Residential Energy Consumption Survey (RECS). The benchmarking exercise [7] concluded that the NZERTF's Energy Use Intensity (EUI) was 23.5% of the average home in the U.S. and 37.5% of single-family homes built since 2000 in the same climatic zone.

This paper presents the performance of the NZERTF during its second year of operation, February 2015 through January 2016, compares the performance of the NZERTF during its two years of operation, and quantifies the impact of weather and operational changes on the NZERTF's energy consumption.

2. Net-Zero Energy Residential Test Facility Design Elements

The NZERTF was designed with multiple systems for test purposes; the building envelope, space conditioning systems, and renewable energy systems that were utilized during the first two years of testing are described in the following sections 2.1-2.6.

2.1 Building Envelope

Schematics of the building envelope components and associated thermal resistance values are shown in Fig. 2. Pettit et al. [8] describes in detail the building envelope and construction techniques. As noted by Kneifel and O'Rear [6], the NZERTF's advanced thermal envelope was responsible for approximately 60% of the energy reduction relative to a Maryland code compliant home.

Blower door tests, conducted at various times since the house was completed, have yielded an average air exchange rate of 0.6 air changes per hour at 50 Pa, <http://www.nist.gov/el/nzertf/bea.cfm>. For comparison, Table 1 gives the target airtightness prescribed by various organizations. As noted by Kneifel and O'Rear [6], the NZERTF's advanced thermal envelope was responsible for approximately 60% of the energy reduction relative to a Maryland code compliant home.

2.2 Space Conditioning System

The space heating and cooling system used for both the first and second years of testing consists of an air-to-air heat pump system incorporating a two-speed scroll compressor and variable speed indoor fan. At the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) rating conditions [9], the cooling capacity is 7.60 kW and the coefficient of performance (COP) is 3.82. In the heating mode at AHRI rating conditions, the unit has a heating capacity of 7.80 kW. The unit has a seasonal energy efficiency ratio SEER - 15.80 Btu/Wh (4.63 W/W) and a heating seasonal performance factor HSPF Region IV - 9.04 Btu/Wh (2.65 W/W). A 10 kW supplemental electric heater was used during the first year, while a 5 kW heater was installed for the second year. A conventional sealed sheet-metal air distribution and return duct system, contained within the conditioned space, is used to distribute conditioned air throughout the house.

During the first year of testing, dehumidification was provided by utilizing the heat pump's dedicated dehumidification cycle. 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.

During the second year of operation, a whole house dehumidifier was used in lieu of the heat pump's dedicated dehumidification cycle. The whole house dehumidifier consists of a duct that pulls air from a wall register located in the living room, a dehumidifier unit, and duct work that supplies the air leaving the dehumidifier to the supply duct leaving the heat pump system. The dehumidifier passes the incoming air over an evaporator coil dropping the air temperature below the dew point of the air. The air is then reheated by passing through the condenser coil before exiting the unit. The unit, tested in accordance with the Association of Home Appliance Manufacturers' Performance Standard for Residential Dehumidifiers [10], has a capacity of 63.9 L/day and an energy factor of 1.81 L/kWh at a flow rate of 14 m³/min (500 CFM) with 26.7°C/60% RH inlet air conditions.

2.3 Ventilation System

Outdoor ventilation air is supplied to the NZERTF via the heat recovery ventilator (HRV). The unit was sized to provide 137 m³/h of outdoor air in accordance with the requirements in ASHRAE Standard 62.2-2010 [11]. The actual outdoor airflow rate provided by the HRV during the first year of operation was approximately 171 m³/h [1,5]. This value, which exceeds the ASHRAE Standard 62.2 requirement by approximately 25 %, resulted from selecting the lowest HRV fan speed (of the six possible) that exceeded the 137 m³/h requirements. During the second year, control of the unit was modified so that it operated for 43 minutes of each hour at 205.2 m³/h to meet, but not exceed, the ASHRAE 62.2 prescribed value. The measured effectiveness of the heat exchanger, 0.76, was determined using temperature and HRV airflow measurements [12].

The house has additional local air exhaust systems comprised of a kitchen exhaust fan and dryer exhaust. The kitchen exhaust fan is activated whenever the cooktop is energized, and the exhaust rate meets the minimum requirement for intermittent local kitchen exhaust in ASHRAE 62.2. Table 2 gives the air changes per hour attributed to the HRV, kitchen exhaust fan, and clothes dryer exhaust.

2.4 Heat Pump, Whole House Dehumidifier, and Heat Recovery Ventilator Controls

Heating and cooling thermostat set points of 21.1 °C and 23.8 °C, respectively, were used for both years. No temperature set backs were used. During the first year, the combined thermostat/humidistat supplied by the heat pump's manufacturer was used to control the heat pump system. This thermostat required the user to set the 1st, 2nd, and 3rd stage temperature differentials and associated time delay intervals. The differential temperatures are relative to the set point temperature and are used to initiate the various stages of heating and cooling. The delay intervals are the maximum amount of time a given stage can operate before energizing the next higher stage. The selected values were chosen to maintain comfortable conditions throughout the year and minimize the use of resistive heat. In the heating mode, 40 minutes was the maximum time the thermostat would permit the heat pump's compressor to operate in its high-speed mode before energizing the electric resistance heat. This control logic resulted in unnecessary usage of electric resistance heat during the first year of

operation. By limiting the second stage heat pump runtime to 40 min, the thermostat would energize the 3rd stage (10 kW electric resistance heat) even though 2nd stage heating was gradually increasing the temperature in the house and able to maintain the indoor temperature within 0.6°C of the thermostat's set point. The humidistat was set to energize the two stages of dehumidification if the measured relative humidity exceeded 50 %. The first stage of dehumidification consists of lowering the indoor fan speed to reduce the temperature of the indoor coil. After 15 minutes, if the first stage does not lower the humidity level to below 50 %, the dedicated dehumidification cycle is used to remove moisture.

During the second year of operation the combined thermostat/humidistat was replaced with a thermostat that activated the 2nd stage of heating or cooling only if the difference between the sensed temperature and set point was greater than 0.6 °C. If the sensed temperature dropped lower than 2.8 °C below the set point, the thermostat energized the electric resistance heat. A separate humidistat, adjacent to the thermostat, activated the whole house dehumidifier if the indoor relative humidity exceeded 50 %.

2.5 Solar Energy Systems

The NZERTF incorporates both a photovoltaic and solar hot water system (SHW). The photovoltaic system consists of thirty-two 320 W photovoltaic modules with a nominal 19.6 % efficiency. The power, voltage, and current at maximum power for the array at Standard Test Conditions (STC) [13] are 10.24 kW, 438 V, and 23.4 A, respectively. Two 5 kW-rated inverters, having a measured weighted efficiency of 95.5 % [14], are used to convert the direct current (DC) into 60 Hz alternating current (AC).

The solar hot water system utilizes two SRCC OG-100 [15] certified single-glazed flat plate thermal collectors, with individual aperture areas of 1.1 m by 2.0 m, and a 303 L storage tank. The slope and intercept of the collector efficiency curve are -4.01 W/m^2 and 0.75 respectively. The thermal collectors are mounted on the porch roof, facing true south at an 18.4° tilt. A 50 % by volume propylene glycol in water solution is used in the solar thermal collector fluid loop. External to the solar storage tank is an insulated cross-flow heat exchanger, two circulating pumps, a controller, and two check valves to prevent reverse thermosyphoning. The hot water leaving the solar storage tank enters a thermostatic mixing valve, set at 49 °C, before entering an auxiliary 189 L downstream heat pump water heater (HPWH). The HPWH is operated in the "Hybrid" mode with a set-point of 49 °C, only activating an integral 3800 W resistive electric element when hot water demand cannot be met by the heat pump.

2.6 Virtual Family

The NZERTF utilizes a 'virtual family' to emulate the energy and hot water consumption of a typical family. The number of occupants, occupancy profiles, water usage, and annual energy consumption of devices within the NZERTF were derived from the Building America Research Benchmark Definition [16]. During both years of evaluation identical energy use/occupant profiles were used.

A ‘virtual family’ of four occupants is emulated within the NZERTF. A minute-by-minute occupancy, lighting, and device usage schedule for each virtual family member is based upon a 7-day detailed narrative as presented in Omar and Bushby [17] and summarized by Kneifel [18]. Electric plug loads that would be found in at least 50 % of all the households in the U.S. were incorporated into the NZERTF [17]. The number of cycles per week for the dishwasher, clothes washer, and the clothes dryer is based on a survey conducted by Proctor and Gamble and obtained from Iglehart et al. [19].

The refrigerator is not subjected to the type of loads that would be present in a typical residence, such as opening doors or adding warm food. In order to compensate, an electrical resistor was placed inside the refrigerator and the power adjusted such that the annual energy consumption of the refrigerator is approximately equivalent to that determined using the U.S. Department of Energy regulatory test method [20], 404 kWh.

Simulating human occupancy requires accounting for the sensible and latent loads. In the NZERTF, sensible loads are simulated by 70 W resistors placed in the bedrooms, kitchen, and the living room areas operated in accordance with the occupancy schedule for each room. To introduce moisture into the NZERTF to represent the latent loads from cooking and the simulated human occupants, an ultrasonic humidifier is used [21]. The electrical energy used to operate the sensible and latent loads associated with the virtual occupants is not considered part of the NZERTF’s energy consumption.

Water consumption in the NZERTF is simulated using the apparatus/techniques described in Davis et. al. [12]. The average daily water consumption for the virtual family was obtained from the average of three domestic hot water studies summarized in [16]. The average daily water usage is 265 L per day not including water consumed by the dishwasher, clothes washer, and toilets.

3 Net-Zero Energy Residential Test Facility Performance

This section compares the performance of the NZERTF for the two years of testing that has been completed to date. The instrumentation, data acquisition system, and measurement uncertainty associated with all measurements are described in detail by Davis et. al [12]. Complete data from Year 2 are available at <https://pages.nist.gov/netzero/> [22,23] Due to failures associated with the data acquisition system, four and five days of data were lost, respectively, during the first year and second years of operation. To compare the NZERTF’s second year energy performance to the first year on an equitable basis, the energy consumption and photovoltaic energy production values for months with missing data were prorated by taking the average daily values for the affected months and multiplying by the number of days in a full month. The adjusted results are presented in Table 3. The percentage of the total energy consumed by the various devices/systems within the NZERTF is shown in Fig. 3.

Adjustments for missing data caused by the data acquisition outages were not made for the measured performance values and metrics associated with the individual systems within the NZERTF such as the solar thermal and photovoltaic systems, the heat pump water heater, the

whole house dehumidifier, and the heat pump used to space condition the house (Tables 4, 5, and 6). Thus, the measured energy consumption values for the months with missing data will differ from the prorated values in Table 3.

Using the prorated values, Table 3, results in an annual energy surplus of 2241 kWh for the second year compared to 1023 kWh for the first year, or an increase of 1218 kWh. The annual energy produced by the photovoltaic system was essentially identical for both years, whereas the energy consumed by the NZERTF during the second year decreased by approximately 10 %. In the following sections, the second-year performance of various systems and electrical loads within the NZERTF will be compared to those previously reported [1] during the first year of operation.

3.1 Photovoltaic Energy Production

Table 4 compares the monthly performance of the NZERTF's photovoltaic array during the first two years of evaluation. For months during which snow or ice was not present, the difference in conversion efficiency between the two years, from incident solar irradiance to direct current energy, is less than 0.3 %. The inverter conversion efficiencies were within 0.4% for any given month, with the second year exhibiting slightly lower values for 11 of the 12 months relative to those measured during the first year. The overall conversion efficiency, incident solar energy to AC energy delivered, was 16.9 % for the second year and 16.8 % for the first year. During the first year of testing, the photovoltaic array was fully or partially covered with snow for all or part of the day for 38 days compared to 26 days during the second year. The annual overall conversion efficiencies are 17.1 % for the second year and 17.4 % for the first year if the days during which snow was present are removed from the analysis.

Remarkably, a difference of less than 0.1 % exists in the annual photovoltaic energy generation between the two years. For the second year, the photovoltaic array generated 14042 kWh compared to 14064 kWh generated during the first year (both values prorated to include the missing days).

3.2 Energy Consumption

The energy consumed by the NZERTF during the second year, 11801 kWh, was 1241 kWh less than the first year's energy consumption, 13042 kWh, Table 3. Both values and the energy consumed by the various devices within the NZERTF for the two years, Fig. 4, have been prorated for the missing days. The peak power demand during the second year is approximately 13 kW compared to a peak of approximately 20 kW during the first year. The peak load during the second year occurred when the heat pump unit was undergoing a defrost cycle (power ≈ 7 kW) at the same time as other large loads such as the clothes dryer (5.5 kW), heat pump water heater resistance elements (4.5 kW), or oven (3.5 kW) were active. The peak load during the second year is less than that during the first year because of the use of smaller resistance elements in the heat pump unit during the second year.

3.2.1 Appliances—Appliances include the refrigerator, dish washer, cooktop, oven, microwave, clothes washer, and clothes dryer. The total appliance energy consumption,

prorated for the missing days, agreed within 2 % for the two years, 1852 kWh and 1894 kWh, for the second and first years, respectively. The greatest difference in appliance energy usage was observed for the clothes dryer, Fig. 4. Compared to the first year, the clothes dryer consumed approximately 12 % less energy during the second year. The decline in the clothes dryer energy usage has been gradual over both years and was further examined. It was speculated that either the mass of the artificial laundry load or the amount of water added to the dryer before each cycle to replicate the moisture content of laundry after washing had decreased; however, these hypotheses were discarded after verifying that neither the amount of water injected into the dryer nor the mass of the laundry load had changed.

3.2.2 Lighting—The prorated lighting energy used over the two periods agreed to within 2 % with the second year being slightly less, 434 kWh versus 442 kWh.

3.2.3 Plug Loads—During the first year the plug loads consumed 2472 kWh, prorated for missing days. During the second year the prorated energy consumed by the plug loads increased approximately 7 % to 2651 kWh. This increase is attributed to instrumentation that was either not monitored or not installed during the first year's study. In an attempt to offset the increased load imposed by the additional instrumentation added to the heat pump during the second year, the standby power of the virtual TV, video box, and game station was decreased by 115 kWh during the second year.

3.2.4 Water Heating System—The water heating system in the NZERTF consists of a SHW system with a downstream HPWH system providing supplemental back up water heating when needed. A detailed description of these two systems can be found in [1]. Table 5 presents the measured performance data for the solar hot water system and heat pump water heater, uncorrected for missing days. Energy used by both the circulators and HPWH were very close between the two years, and the total measured energy needed to provide hot water was nearly identical, 1434 kWh for year two and 1432 kWh for year one. The projected yearly values, prorated for missing days, gives a total of 1450 kWh for the second year and 1451 kWh for the first year, Table 3.

The solar thermal water heater provided a similar fraction of the total energy required to meet the annual hot water demand, 52 % in the second year and 54 % in the first year. This result was obtained despite a malfunction during February of the second year that resulted in the circulators not operating properly. Of the total energy consumed by the heat pump water heater, 71 kWh (6 %) was consumed by auxiliary resistive heat in the second year, in contrast to 137 kWh (12 %) in the first year. The larger resistive heat use in year one is partially attributed to a control wire becoming dislodged, preventing operation of the heat pump water heater for a nine-day period.

3.2.5 Heat Recovery Ventilator—The electrical energy consumed by the fans within the HRV, prorated for the missing days, was 521 kWh for the first year versus 411 kWh for the second year. This reduction was an artifact of the HRV fans running continuously during year one compared to 43 min/hr during the second year. The measured effectiveness of the HRV was essentially equivalent during the two years of operation, 0.76.

3.2.6 Heating, Cooling, Ventilation, and Dehumidification Systems—The energy consumed to meet the space-conditioning loads accounted for most of the energy consumption reduction from year one, 6785 kWh (heat pump with active dehumidification, HRV) to year two 5414 kWh (heat pump, HRV, whole house dehumidifier), Fig. 4. The most significant reduction was the energy consumed by the heat pump to heat the NZERTF, 2347 kWh for the second year compared to 3783 kWh for the first year, Figure 4. The whole house dehumidifier, not present during the first year, was responsible for 465 kWh of energy consumption during the second year.

The milder winter, reduced ventilation rate, and the improved control logic within the thermostat used during the second year all contributed to reducing the energy needed to heat the NZERTF during the second year. For the months of November, December, and January the heating degree days were significantly less than those experienced during the first year, Fig. 5. The only exception is February, where the heating degree days were greater during the second year due to surprisingly cold weather conditions. Unlike the heating degree days which decreased by 314 compared to the first year, the cooling degree days increased to 2519 °C Days for the second year versus 2311 °C Days for the first year. To separate the impact of the weather and reduced ventilation rate from the changes in the thermostat's control logic and the mechanism used to dehumidify the NZERTF, it is necessary to project the energy consumption of the NZERTF, in its year one configuration, to what the energy consumption would have been if subjected to year two weather conditions and ventilation rate.

The NZERTF EnergyPlus model [24] and Actual Meteorological Year (AMY) weather files for both the first and second years were used to predict the NZERTF's energy consumption in its year one configuration. The model had been previously compared to measured data for the year one configuration and predicted the overall measured energy consumption within 4 % [25]. The simulation results show that the first year's NZERTF energy consumption would have decreased by 717 kWh if the second year's weather conditions and ventilation rate had been present, reducing the first year's measured total energy consumption from 13042 kWh to a projected value of 12325 kWh. The remaining difference in energy consumption between the two years, 524 kWh is attributed to the changes in the control logic that significantly decreased the use of resistive heat and the fact that the active dehumidification mode was not utilized during the cooling season of the second year, both of which decrease energy consumption. However, the use of the whole house dehumidifier during the second year could potentially increase the second year's energy consumption since it adds to the space conditioning load, and its efficiency is less than that of the dedicated dehumidification mode associated with the air-to-air heat pump, as shown by the L/kWh metric in Table 6. Detailed simulations are planned in the future to better quantify the impacts of the various changes that were made prior to the second year of operation. The following sections attempt to quantify the impact of the equipment and control logic changes between the two years of evaluation.

3.3 Whole House Dehumidifier

Unlike the previously discussed devices and systems, a totally different approach was used to dehumidify the NZERTF during the second year. Accordingly, the approach used during each of the two years and the resulting performance is discussed in detail.

During the first year of testing, the dedicated dehumidification mode of the heat pump unit was used to provide moisture control. A whole house dehumidifier, in lieu of the dedicated dehumidification cycle, was used to provide moisture control during the second year. Table 6 presents the performance metrics associated with the whole house dehumidifier and the air-to-air heat pump system's dedicated dehumidification mode. The values are the hours for each month that the heat pump ran in the dedicated dehumidification mode during the first year and the hours that the whole house dehumidifier operated for each month during the second year. Table 6 also includes the liters of water removed per kWh of energy consumed. These data have not been prorated to reflect the four days of missing data during the first year and five days during the second year of operation.

A fundamental difference between these two modes of dehumidification is the manner in which they reject the sensible heat generated during the dehumidification process. During the first year, when the dedicated dehumidification cycle of the air-to-air heat pump was used, the sensible heat generated was rejected outdoors by means of the outdoor condenser. The whole house dehumidifier, used during the second year, rejects the sensible heat generated during dehumidification inside the house. The rejected heat from the whole house dehumidifier increases the cooling load during space cooling months and decreases the space heating load if its operation coincides with time intervals that space heating is required. During the second year, the whole house dehumidifier consumed 465 kWh of energy and dissipated this amount in the form of sensible heat into the house. The vast majority, over 80 %, was dissipated into the NZERTF during cooling dominated months, May through October. The net result was an increase of 385 kWh of additional load during the cooling season and an 80 kWh reduction in the space heating load during heating dominated months.

During the first year of operation the dedicated dehumidification mode of the air-to-air heat pump was utilized. Whenever the unit operated in this mode, the COP of the air-to-air heat pump unit decreased dramatically to a value of less than 1, Table 6. It is interesting to note that the amount of time the heat pump operated in the dehumidification mode, 133 hours, was similar to the run time of the whole house dehumidifier during year two, 126 hours.

Figure 6 plots the quantity of water removed per unit of energy consumed for the air-to-air heat pump's dedicated dehumidification cycle used during year one and the whole house dehumidifier used during year two. Data are only included for the months that both units ran for greater than 20 hours to exclude months when the standby energy was dominant. For all months the dedicated dehumidification cycle removed a greater quantity of water per unit of energy consumed than the whole house dehumidifier. However, whenever the heat pump operates in its dedicated dehumidification mode, the heat pump's COP is significantly reduced. Figure 7 shows the comparison of year one COP's for the heat pump with and without the dedicated dehumidification cycle operating for the same months used in Figure

6. The reduction in COP resulting from the heat pump operating in the dedicated dehumidification mode is also apparent when the cooling COPs are compared for the first year of operation, in which the heat pump's dedicated dehumidification mode was used to provide humidity control, to the heat pump's COP during the second year when the unit was not allowed to operate in its dedicated dehumidification mode, Fig. 7.

3.4 Heat Pump Control Logic

Fig. 8 compares the heat pump's coefficient of performance for the two heating seasons. Other than the months where very little runtime occurred (October for both years and April during the second year of testing) and the month of February where the second year was significantly colder than the first, Fig. 5, the heating mode COP values for the second year exceeded those observed during the first year of testing. Of particular interest is the amount of resistive heat used during each of the two years, Fig. 9. Here, resistive heat refers to heating elements in the indoor unit used as supplements to the heat pump. During the first year the total energy consumed by the resistive heat was 1157 kWh compared to a total of 163 kWh during the second year. Although a portion of this can be attributed to milder weather conditions during year two, the vast majority is attributed to the improved control logic used in the thermostat. The reduced use of resistance heat is attributed to the change in control logic described in the Heat Pump, Whole House Dehumidifier, and Heat Recovery Ventilator Controls Section. In fact, the electric resistance heat in the indoor unit was never energized during the entire second year in order to meet the space heating thermal load. Only when the heat pump went into the defrost cycle did the control logic energize the resistive heaters.

4 Conclusions

The NZERTF successfully completed its second year of operation producing a 2241 kWh surplus of energy compared to the 1023 kWh surplus produced during the first year of operation. The energy provided by the NZERTF's rooftop photovoltaic array during the two years was essentially identical. The energy consumed by the appliances, plug loads, lighting, and domestic water heating equipment was similar for both years. The greater energy surplus is a result of reduced energy consumption by the space conditioning and ventilation equipment during the second year attributed to milder weather conditions, reduced ventilation, and improved heat pump thermostat control logic.

According to EnergyPlus computer simulations, 856 kWh of the 1218 kWh increase in surplus energy was attributable to the milder weather conditions experienced during the second year and the ventilation rate being reduced from 171 m³/h to 137 m³/h. The remaining amount is attributed to the use of a thermostat with control logic that minimized the use of electric resistance heat and not utilizing the heat pump's dedicated dehumidification mode. The heat pump's heating coefficient of performance for the second year was significantly higher than the first year, primarily a result of less resistive heat being used due to a change in the thermostat's control logic. In fact, the only time electric resistive heat was used during the second season was during defrost cycles. During the cooling

season the heat pump's coefficient of performance was also higher during the second year as a result of not utilizing the heat pump's dedicated dehumidification mode.

The use of a whole house dehumidifier resulted in an increased space conditioning load during the cooling months due to the sensible heat being rejected into the living space. In addition, the efficiency of dehumidifying with the whole house dehumidifier was less than the efficiency achieved using the air-to-air heat pump's dedicated dehumidification cycle.

To fully capture the interrelationships between the various space conditioning systems – heat pump, heat recovery ventilation system, and whole house dehumidifier, future work will focus on predicting the performance of these various systems using tools such as TRNSYS [26].

References

1. Fanney A, Payne W, Ullah T, Ng L, Boyd M, Omar F, Davis M, Skye H, Dougherty B, Polidoro B, Healy W, Kneifel J, Pettot B. Net-zero and beyond! Design and performance of NIST's net-zero energy residential test facility. *Energy and Buildings*. 2015; 101:95–109.
2. Kneifel J. Life-Cycle cost comparison of the NIST net zero energy residential test facility for a Maryland code compliant design. *NIST Special Publication*. 2014; 1172
3. Kneifel J, O'Rear E. Comparing the energy and economic performance of the NIST NZERTF design across the mixed-humid climate zone. *NIST Special Publication*. 2015; 1603
4. Poppendieck D, Ng L, Persily A, Hodgson A. Long term indoor air quality monitoring in a net-zero energy residence designed with low emitting interior products. *Building and Environment*. 2015
5. Ng L, Payne W. Energy use consequences of ventilating a Net-Zero energy house. *Applied Thermal Engineering*. 2015; 96
6. Kneifel J, O'Rear E. Sustainability Performance of the NIST Net-Zero Energy Residential Test Facility Relative to a Maryland Code-Compliant Designs. *NIST Technical Note*. 2015; 1187
7. Ullah, T., Poppendieck, D., Healy, W., Fanney, A., Teichman, K. ACEEE Summer Study on Energy Efficiency in Buildings. Pacific Grove, CA: 2016. Energy and indoor air quality benchmarking of the NIST Net-zero energy residential test facility (NZERTF).
8. Pettit B, Gates C, Fanney AH, Healy WM. Design challenges of the NIST net zero energy residential test facility. *NIST Technical Note*. 2015; 1847
9. AHRI. Standard for performance rating of unitary air-conditioning and air-source heat pump equipment, Air-Conditioning, Heating, and Refrigeration Institute, 2111 Wilson Boulevard, Suite 500. AHRI; Arlington, VA, 22201: 2008. AHRI 2008 Standard 210/240
10. AHAM. Dehumidifiers, Association of Home Appliance Manufacturers, 1111 19th Street, NW, Suite 402. AHAM; Washington, DC, 20036: 2008. AHAM 2008 Standard DH-1-2008
11. ASHRAE. ANSI/ASHRAE Standard 62.2-2010: Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; Atlanta, GA, 30329: 2010.
12. Davis MW, Healy WM, Boyd M, Payne WV, Skye H, Ng L, Ullah T. Monitoring techniques for the net-zero energy residential test facility. *NIST Technical Note*. 2014; 1854
13. International Electrotechnical Commission (IEC). Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval. International Electrotechnical Commission (IEC); Geneva, Switzerland: 2005. IEC Standard 61215
14. Bower W, Whitaker C, Erdman W, Behnke M, Fitzgerald M. Performance test protocol for evaluating inverters used in grid-connected photovoltaic systems. 2004
15. SRCC™ Standard 100. Test Methods and Minimum Standards for Certifying Solar Collectors. Solar Rating and Certification Corporation; Cocoa, FL: 2012.
16. Hendron, R. Building America Research Benchmark Definition. National Renewable Energy Laboratory; Golden, CO: 2008. Technical Report No NEEL/TR 550-44816

17. Omar F, Bushby ST. Simulating occupancy in the NIST net-zero energy residential test facility. NIST Technical Note. 2013; 1817
18. Kneifel JD. Annual whole building energy simulation of the NIST net-zero energy residential test facility. NIST Technical Note. 2012; 1767
19. Iglehart C, Milesi-Ferretti N, Galler M. Consumer use of dishwashers, clothes washers, and dryers: data needs and availability. NIST Technical Note. 2011; 1696
20. U.S. Department of Energy's Regulatory Test Method, 10CFR430, Subpart B, Appendix A, 47FR 34526, 2011.
21. Fang, X., Christensen, D., Barker, G., Hancock, E. Field Test Protocol: Standard Internal Load Generation for Unoccupied Test Homes, Building Technologies Program. U.S. Department of Energy; 2011.
22. Healy, William M., Fanney, A Hunter, Dougherty, Brian P., Ng, Lisa, Payne, Vance, Ullah, Tania, Omar, Farhad. Performance Data from the NIST Net-Zero Energy Residential Test Facility. Journal of Research of the National Institute of Standards and Technology. 2017 Jan.122doi: 10.6028/jres.122.014
23. Healy, William, Omar, Farhad, Ng, Lisa, Ullah, Tania, Payne, William, Dougherty, Brian, Fanney, A Hunter. Net Zero Energy Residential Test Facility Instrumented Data; Year 2. National Institute of Standards and Technology. 2016. <https://doi.org/10.18434/T46W2X>
24. Kneifel J. Annual whole building energy simulation of the NIST net zero energy residential test facility. NIST Technical Note. 2012; 1767
25. Kneifel J. Simulated versus measured energy performance of the NIST net zero residential test facility. NIST Special Publication. 2015; 1182
26. TRNSYS 17. A TRaNsient SYstems Simulation Program. TRNSYS. Solar Energy Laboratory; 2013. <http://sel.me.wisc.edu/trnsys/>

a

b

Fig. 1. Net-zero energy residential test facility (NZERTF). (a) Image of NZERTF, (b) First Floor (left) and Second Floor (right) Plans

Fig. 2.
Building envelope components and associated R-values.

Fig. 3.
Percent of total energy consumed by various end uses/devices within the NZERTF.

Fig. 4.
Comparison of prorated end use energy consumption.

Fig. 5.
Comparison of heating and cooling degree days.

Fig. 6.
Comparison of dehumidification efficiency.

Fig. 7.

Comparison of heat pump's COP during two cooling seasons.

Fig. 8.

Comparison of heat pump coefficient of performance for the two heating seasons.

Fig. 9.

Comparison of energy consumed by heat pump and resistive heat during the two heating seasons.

Table 1

Current Airtightness Values Prescribed by Various Organizations

Guideline/Standard	Target Airtightness (h^{-1} at 50 Pa)
NZERTF	0.6
Passiv House ^a	0.6
LEED BD+C: Homes v4 ^b	2.0
DOE Challenge Home ^c	2.7
ENERGY STAR v3.1 (rev. 06) ^d	3.0
ICC 700 Green Building Standard (testing option) ^e	7.5

^aPHI, Passive House requirements, [Web page], <http://www.passiv.de/en/index.php>

^bU.S. Green Building Council, LEED BD+C: Homes, <http://www.usgbc.org/credits/homes/v4>

^cDOE, DOE Challenge Home (Rev. 03), Amer. Soc. Heat. Refrig. Air Cond. Eng., Washington, D. C. 2013.

^dEPA, ENERGY STAR Certified Homes, Version 3.1 (Rev. 06), U. S. Environmental Protection Agency.

^eNAHB/ICC, ICC 700-2012 National Green Building Standard, Washington, D. C. 2012.

Table 2

Air Changes Per Hour Attributed to HRV, Kitchen Exhaust Hood, and Clothes Dryer

Ventilation Appliance	On-time airflow (h^{-1})	Effective airflow (h^{-1})
HRV	0.16	0.11
Kitchen exhaust hood	0.14	0.0027
Clothes Dryer	0.05	0.0007

The two columns show the on-time airflow and the effective airflow, which accounts for each appliances' off-time. The HRV is on for 43 min out of every hour, every day of the week (0.6667 of a week). The kitchen exhaust hood is on for 18 min each time, 11 times per week (0.0196 of a week). The dryer is on for 30 min each time, 5 times per week (0.0149 of a week). The on-time airflow multiplied by the fraction on-time is the last column, effective airflow.

Table 3

Monthly NZERTF Thermal Loads and Energy Consumption (kWh) by End Use

Upper Values – July 2013 through June 2014¹Lower Values (*Italics*) – February 2015 through January 2016²

Month/Year	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Annual
Heating Load – Yr. 1	0.0	0.0	0.0	56.4	830.4	1351.0	2156.9	1634.7	1423.5	252.7	0.0	0.0	7705.7
<i>Heating Load – Yr. 2</i>	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>24.1</i>	<i>160.2</i>	<i>313.5</i>	<i>1642.7</i>	<i>1868.0</i>	<i>1139.6</i>	<i>158.9</i>	<i>0.0</i>	<i>0.0</i>	<i>5307.3</i>
Cooling Load – Yr. 1	2122.9	1659.8	937.2	306.4	1.7	0.0	0.0	0.0	0.0	66.8	603.0	1559.7	7257.5
<i>Cooling Load – Yr. 2</i>	<i>2379.4</i>	<i>2144.6</i>	<i>1651.6</i>	<i>141.5</i>	<i>42.0</i>	<i>41.8</i>	<i>0</i>	<i>0.0</i>	<i>0.0</i>	<i>51.9</i>	<i>1203.3</i>	<i>1856.7</i>	<i>9512.8</i>
DHW Load – Yr. 1	252.4	259.7	238.2	268.5	283.2	325.9	343.1	330.0	340.5	300.3	276.9	250.6	3469.3
<i>DHW Load – Yr. 2</i>	<i>241.8</i>	<i>234.7</i>	<i>229.6</i>	<i>257.6</i>	<i>268.0</i>	<i>282.2</i>	<i>288.1</i>	<i>307.4</i>	<i>339.9</i>	<i>303.9</i>	<i>279.8</i>	<i>246.9</i>	<i>3279.9</i>
Heat Pump Heating – Yr. 1	0.0	0.0	0.0	33.6	396.4	581.5	1254.8	753.1	650.4	113.2	0.0	0.0	3783.1
<i>Heat Pump Heating – Yr. 2</i>	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>18.4</i>	<i>70.8</i>	<i>118.7</i>	<i>719.2</i>	<i>874.2</i>	<i>468.9</i>	<i>74.5</i>	<i>2.4</i>	<i>0.0</i>	<i>2347.2</i>
Heat Pump Cooling – Yr. 1	700.8	573.5	345.4	142.3	15.7	0.0	0.0	0.0	0.0	13.6	177.7	511.3	2480.3
<i>Heat Pump Cooling – Yr. 2</i>	<i>525.8</i>	<i>480.2</i>	<i>368.2</i>	<i>40.5</i>	<i>10.7</i>	<i>10.1</i>	<i>0</i>	<i>0.0</i>	<i>0.0</i>	<i>18.2</i>	<i>320.0</i>	<i>416.5</i>	<i>2190.3</i>
HPWH – Yr. 1	53.3	84.4	57.0	82.5	129.8	156.3	142.8	125.0	120.7	72.7	55.2	46.1	1125.8
<i>HPWH – Yr. 2</i>	<i>58.3</i>	<i>50.9</i>	<i>64.2</i>	<i>95.8</i>	<i>104.6</i>	<i>121.4</i>	<i>125.4</i>	<i>148.5</i>	<i>144.5</i>	<i>79.0</i>	<i>58.0</i>	<i>67.1</i>	<i>1117.9</i>
Solar System Circulators – Yr. 1	35.7	32.3	31.4	24.2	22.0	18.2	20.4	19.8	22.6	29.0	34.3	34.8	324.7
<i>Solar System Circulators – Yr. 2</i>	<i>36.2</i>	<i>36.5</i>	<i>32.3</i>	<i>25.9</i>	<i>22.7</i>	<i>18.5</i>	<i>18.9</i>	<i>18.9</i>	<i>28.3</i>	<i>28.5</i>	<i>34.9</i>	<i>30.7</i>	<i>332.5</i>
<i>Whole House Dehumidifier – Yr. 2</i>	<i>100.7</i>	<i>72.2</i>	<i>60.2</i>	<i>76.2</i>	<i>31.6</i>	<i>39.4</i>	<i>0.0</i>	<i>3.0</i>	<i>3.3</i>	<i>3.2</i>	<i>3.3</i>	<i>72.0</i>	<i>465.1</i>
Lighting – Yr. 1	37.5	38.0	36.1	37.8	36.3	36.6	36.9	32.9	36.2	38.1	39.5	35.6	441.5
<i>Lighting – Yr. 2</i>	<i>37.0</i>	<i>36.4</i>	<i>35.4</i>	<i>36.2</i>	<i>35.4</i>	<i>36.6</i>	<i>35.9</i>	<i>33.5</i>	<i>38.2</i>	<i>36.3</i>	<i>36.6</i>	<i>36.4</i>	<i>433.7</i>
Plug Loads – Yr. 1	202.5	199.2	199.7	210.2	208.5	210.2	214.0	193.8	216.7	206.3	208.2	202.5	2471.8
<i>Plug Loads – Yr. 2</i>	<i>221.1</i>	<i>225.6</i>	<i>215.6</i>	<i>226.3</i>	<i>218.1</i>	<i>223.3</i>	<i>227.6</i>	<i>206.2</i>	<i>227.8</i>	<i>219.0</i>	<i>226.3</i>	<i>214.4</i>	<i>2651.3</i>
Heat Recovery Ventilator – Yr. 1	42.4	42.4	42.3	44.4	43.7	44.3	46.4	38.7	45.3	42.8	45.4	43.1	521.2
<i>Heat Recovery Ventilator – Yr. 2</i>	<i>34.9</i>	<i>34.8</i>	<i>33.7</i>	<i>33.8</i>	<i>32.6</i>	<i>33.7</i>	<i>36.0</i>	<i>33.9</i>	<i>35.7</i>	<i>33.3</i>	<i>34.8</i>	<i>34.1</i>	<i>411.4</i>
Refrigerator – Yr. 1	36.2	36.1	36.0	35.4	32.3	34.0	34.4	31.1	34.7	34.2	35.9	35.7	416.0
<i>Refrigerator – Yr. 2</i>	<i>37.0</i>	<i>36.3</i>	<i>36.2</i>	<i>36.3</i>	<i>34.4</i>	<i>36.1</i>	<i>34.8</i>	<i>31.3</i>	<i>35.3</i>	<i>34.2</i>	<i>36.3</i>	<i>35.2</i>	<i>423.3</i>
Dish Washer – Yr. 1	7.8	7.6	7.8	7.8	8.8	8.6	8.6	7.8	8.9	8.0	7.9	7.9	97.5
<i>Dish Washer – Yr. 2</i>	<i>8.1</i>	<i>8.3</i>	<i>7.6</i>	<i>8.7</i>	<i>8.4</i>	<i>8.0</i>	<i>9.0</i>	<i>7.9</i>	<i>8.6</i>	<i>7.8</i>	<i>8.4</i>	<i>7.7</i>	<i>98.5</i>
Cooktop – Yr. 1	19.2	19.6	19.7	19.2	19.6	19.7	19.3	17.8	20.9	19.2	20.1	19.4	233.7

Month/Year	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Annual
<i>Cooktop – Yr. 2</i>	19.2	20.9	18.8	20.8	19.6	18.9	21.2	18.0	20.1	18.8	20.9	18.8	236.0
Oven – Yr. 1	30.0	32.2	31.7	30.0	33.7	31.9	30.0	29.3	35.8	31.7	33.7	31.7	381.7
<i>Oven – Yr. 2</i>	30.0	35.8	29.8	36.8	31.7	28.1	36.8	29.3	31.9	29.8	35.8	29.3	385.1
Clothes Washer – Yr. 1	5.2	5.5	6.2	6.2	6.1	6.3	6.2	5.6	6.4	6.0	6.1	6.0	71.8
<i>Clothes Washer – Yr. 2</i>	6.0	6.3	5.9	6.0	5.7	5.9	6.4	5.5	5.9	5.8	6.3	5.7	71.4
Clothes Dryer – Yr. 1	47.6	47.5	45.9	44.8	46.8	46.9	45.7	41.2	50.8	44.1	44.2	44.0	549.5
<i>Clothes Dryer – Yr. 2</i>	39.0	46.1	40.0	43.0	40.9	37.7	44.0	37.6	41.7	39.7	43.1	36.8	489.6
Microwave – Yr. 1	12.3	12.4	12.3	12.5	12.2	12.4	12.6	11.4	12.7	12.2	9.2	11.1	143.3
<i>Microwave – Yr. 2</i>	12.5	12.6	12.1	12.5	12.3	12.5	12.6	11.3	12.6	12.1	12.6	11.9	147.6
Total Energy Consumed – Yr. 1	1230.5	1130.7	871.5	730.9	1011.9	1206.9	1872.1	1307.5	1262.1	671.1	717.4	1029.2	13041.9
<i>Total Energy Consumed – Yr. 2</i>	1165.8	1102.8	960.0	717.3	679.5	748.9	1327.9	1459.3	1102.9	640.3	879.7	1016.6	11800.8
Total PV AC Energy – Yr. 1	1528.3	1416.7	1431.0	1016.8	858.0	477.4	806.0	747.6	988.9	1458.0	1664.7	1671.0	14064.4
<i>Total PV AC Energy – Yr. 2</i>	1562.4	1596.5	1263.0	1047.8	822.0	576.6	796.7	736.4	1054.0	1458.0	1742.2	1386.0	14041.6

¹ Values have been prorated in the month of August 2013 to take into account the five missing days (Aug 2-6).

² Values have been prorated for the months of October 2015 and January 2016 to take into account the four missing days (Oct 20-22) and Jan 26th.

Table 4

Monthly Photovoltaic System Performance
 Upper Values – July 2013 through June 2014
 Lower Values (*Italics*) – February 2015 through January 2016

Month	Jul	Aug	Sept	Oct	Nov	Dec ^a	Jan ^a	Feb ^a	Mar ^a	Apr	May	Jun
Average Daily Incident Solar Energy on Array ^b (kWh) Average Daily Solar Insolation on Array ^b (Wh/m ²)	292.4	270.1	283.0	190.3	160.0	108.0	149.7	183.3	207.3	271.8	309.1	325.0
	296.8	305.5	251.5	195.5	155.4	104.5	155.8	186.3	206.6	272.7	326.3	270.5
	5604	5176	5424	3648	3067	2069	2868	3513	3972	5209	5924	6228
	5688	5855	4820	3746	2978	2003	2986	3569	3960	5226	6252	5183
Average Ambient Temperature (C)	25.7	23.6	19.7	15.0	6.8	4.3	-1.9	1.1	4.1	12.7	18.7	23.6
	25.2	24.5	22.2	13.7	12.0	10.6	1.0	-3.3	5.1	13.6	21.1	23.3
Average Cell Temperature During Energy Generation (C)	38.6	36.7	35.1	26.5	15.9	11.1	7.2	10.8	15.1	24.2	32.8	37.6
	38.5	39.3	27.1	24.9	16.3	17.7	10.1	6.7	16.5	25.1	35.2	35.1
									33.5			
Average Daily Delivered DC Energy (kWh)	51.4	47.8	49.8	34.4	30.0	16.3	27.4	27.9	35.7	50.9	56.1	58.2
	52.8	53.9	44.2	35.5	28.8	19.6	27.1	27.8		51.0	58.8	48.5
Array Efficiency (%)	17.6	17.7	17.6	18.1	18.8	15.0	18.3	15.2	16.2	18.7	18.1	17.9
	17.8	17.7	17.6	18.2	18.5	18.8	17.4	14.9	17.3	18.7	18.0	17.9
Average Daily Delivered AC Energy (kWh)	49.3	45.7	47.7	32.8	28.6	15.4	26.0	26.7	31.9	48.6	53.7	55.7
	50.4	51.5	42.1	33.8	27.4	18.6	25.7	26.3	34.0	48.6	56.2	46.2
Inverter Efficiency (%)	95.9	95.6	95.8	95.5	95.3	94.5	95.1	95.4	95.2	95.6	95.7	95.7
	95.5	95.5	95.4	95.3	95.1	94.7	94.9	94.8	95.1	95.3	95.5	95.4

^aFor 8 days in December 2013, 8 days in January 2014, 12 days in February 2014, and 10 days in March 2014 the PV array was fully or partially covered with snow. If these days had been excluded the array efficiencies would have been 19.2%, 19.7%, 19.5%, and 19.2%, respectively.

For 12 days in February 2015, 8 day in March 2015, and 6 days in January 2016, the PV array was fully or partially covered with snow. If these days had been excluded, the array efficiencies would have been 19.8%, 19.1%, and 19.4%, respectively.

^bThe Average Daily Incident Solar Energy on Array was determined using the framed area of an individual module (1.63 m²) multiplied by the number of modules (32).

Table 5

Monthly Solar Hot Water and Heat Pump Water Heater System Performance
 Upper Values – July 2013 through June 2014
 Lower Values (Italics) – February 2015 through January 2016

Month	Jul ^a	Aug ^{b,c}	Sept ^b	Oct ^d	Nov ^e	Dec ^{e,f}	Jan ^{d,f}	Feb ^g	Mar ^g	Apr	May	Jun	Annual Summary
Average Outdoor Temp.(C) Yr. 1	25.7	23.6	19.7	15.1	6.8	4.4	-1.8	1.1	4.1	12.6	18.7	23.6	12.8
Average Outdoor Temp.(C) Yr. 2	25.2	24.5	22.2	13.7	12.0	10.6	1.1	-3.2	5.1	13.6	21.2	23.3	14.1
Avg. Mains Water Temp.(C)Yr. 1	22.9	22.8	23.0	21.1	18.8	16.8	15.4	14.5	14.9	16.0	18.8	20.7	18.8
Avg. Mains Water Temp.(C) Yr. 2	22.3	22.8	23.0	22.3	21.1	19.9	19.0	16.9	16.7	17.9	20.0	21.6	20.3
Energy Dlv'd Solar Tank (kWh) Yr. 1	282.6	151.1	249.7	190.6	139.9	96.1	113.4	148.5	188.7	279.4	299.4	304.9	2444.4
Energy Dlv'd Solar Tank (kWh) Yr. 2	266.9	269.9	215.5	140.4	130.2	94.5	93.7	39.2	123.4	274.0	332.1	244.6	2224.6
Solar Circulator E _{solar} (kWh) Yr.1	35.7	27.1	31.4	24.2	22.0	18.2	20.4	19.8	22.6	29.0	34.3	34.8	319.6
Solar Circulator E _{solar} (kWh) Yr. 2	36.2	36.5	32.3	23.4	22.7	18.5	18.3	18.9	28.3	28.5	34.9	30.7	329.3
Energy Used HPWH E _{HP} (kWh) Yr1	53.3	70.8	57.0	82.5	129.8	156.3	142.8	125.0	120.7	72.7	55.2	46.1	1112.2
Energy Used HPWH E _{HP} (kWh) Yr. 2	58.3	50.9	64.2	86.6	104.6	121.4	121.4	148.5	144.5	79.0	58.0	67.1	1104.6
Energy HPWH Resistive (kWh) Yr. 1	0.0	5.8	3.2	3.2	44.3	36.1	13.9	14.2	12.8	3.3	0.6	0.0	137.4
Energy HPWH Resistive (kWh) Yr.2	0.0	0.0	2.1	5.0	3.8	8.5	11.5	18.7	16.7	3.3	0.0	1.2	71.0
Energy HPWH Q _{del,HP} (kWh) Yr. 1	42.1	107.9	68.3	118.7	172.0	244.0	240.2	207.7	187.3	84.4	54.7	35.3	1562.6
Energy HPWH Q _{del,HP} (kWh) Yr. 2	53.3	41.8	71.5	124.5	157.7	201.4	191.5	254.5	231.9	94.4	50.1	73.7	1546.1
Total Hot Water, Q _{load} (kWh) Yr. 1	252.4	217.8	238.2	268.5	283.2	325.9	343.1	330.0	340.5	300.3	276.9	250.6	3427.5
Total Hot Water, Q _{load} (kWh) Yr. 2	241.8	234.7	229.6	232.7	268.0	282.2	278.8	307.4	339.9	303.9	279.8	246.9	3245.7
Solar Fraction, SF (Yr. 1	0.83	0.50	0.71	0.56	0.39	0.25	0.30	0.37	0.45	0.72	0.80	0.86	0.54
Solar Fraction, SF (Yr. 2	0.78	0.82	0.69	0.46	0.41	0.29	0.31	0.17	0.32	0.69	0.82	0.70	0.52
Solar Energy Factor, SEF (Yr. 1	3.17	2.23	2.69	2.52	1.86	1.87	2.10	2.28	2.38	2.95	3.09	3.10	2.39
Solar Energy Factor, SEF (Yr. 2	2.56	2.69	2.38	2.12	2.11	2.02	2.00	1.93	2.12	2.83	3.01	2.52	2.26

^aData loss on 7/1/2013 prevented calculation of Energy Delivered and Hot Water Load values for that day; therefore, SEF for July is computed for 7/2/2013 – 7/31/2013.

^bBetween 8/24/2013 and 9/3/2013, the pumps of the solar thermal water heater heat exchanger were not operational due to failure of electrical connection to glycol circulating pump.

^cMissing data between 8/2/2013 and 8/6/2013 due to failure of data acquisition system.

^dMissing data between 10/20/2015 and 10/22/2015 and 1/26/2016 due to failure of data acquisition system.

^eBetween 11/25/2013 and 12/5/2013, the heat pump of the heat pump water heater was not operational due to a control wire being disconnected.

^fBetween 12/29/2015 and 1/4/2016, HPWH controls were suspended due to a fault.

^gBetween 2/19/2015 and 3/16/2015, solar heat exchange was not operational due to closed valve.

$$h_{SF} = 1 - (Q_{del,HP}/Q_{load}) \cdot SEF = Q_{load}/(E_{solar} + E_{HP})$$

Table 6

Monthly Air-to-Air Heat Pump and Whole House Dehumidifier Performance
 Upper Values – July 2013 through June 2014
 Lower Values (*Italics*) – February 2015 through January 2016

Month	Jul	Aug ^a	Sep	Oct ^b	Nov	Dec	Jan ^b	Feb	Mar	Apr	May	Jun
<u>Thermal Load^c(kWh)</u>												
Heating Mode Yr.1	0.0	0.0	0.0	56.4	832.1	1351.0	2156.9	1634.7	1423.5	252.7	0.0	0.0
Heating Mode Yr. 2	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>21.8</i>	<i>160.2</i>	<i>313.5</i>	<i>1589.8</i>	<i>1868.0</i>	<i>1139.6</i>	<i>158.9</i>	<i>0.0</i>	<i>0.0</i>
Cooling Mode Yr. 1	2122.9	1392.1	937.2	306.4	1.7	0.0	0.0	0.0	0.0	66.8	603.0	1559.7
Cooling Mode Yr. 2	<i>2379.4</i>	<i>2144.6</i>	<i>1651.6</i>	<i>127.8</i>	<i>42.0</i>	<i>41.8</i>	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>51.9</i>	<i>1203.3</i>	<i>1856.7</i>
<u>Heat Pump Energy Usage (kWh)</u>												
Heating Mode Yr. 1	0.0	0.0	0.0	33.6	396.4	581.5	1254.8	753.1	650.4	113.2	0.0	0.0
Heating Mode Yr. 2	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>16.6</i>	<i>70.8</i>	<i>118.7</i>	<i>696.0</i>	<i>874.2</i>	<i>468.9</i>	<i>74.5</i>	<i>2.4</i>	<i>0.0</i>
Cooling Mode Yr. 1	700.8	481.0	345.5	142.3	15.7	0.0	0.0	0.0	0.0	13.6	177.7	511.3
Cooling Mode Yr. 2	<i>525.8</i>	<i>480.2</i>	<i>368.2</i>	<i>36.6</i>	<i>10.7</i>	<i>10.1</i>	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>18.2</i>	<i>320.0</i>	<i>416.5</i>
Resistive Heat Yr. 1	0.0	0.0	0.0	13.6	103.0	117.0	547.6	196.4	169.4	10.2	0.0	0.0
Resistive Heat Yr. 2	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>0.7</i>	<i>1.0</i>	<i>2.7</i>	<i>55.9</i>	<i>75.3</i>	<i>26.7</i>	<i>0.6</i>	<i>0.0</i>	<i>0.0</i>
Avg. Outdoor Temp Yr. 1	26.6	24.6	20.7	15.5	7.1	4.5	-1.5	1.0	4.1	13.1	19.7	24.5
Avg. Outdoor Temp Yr. 2	<i>25.9</i>	<i>25.3</i>	<i>22.6</i>	<i>13.6</i>	<i>11.2</i>	<i>9.9</i>	<i>0.4</i>	<i>-3.2</i>	<i>5.0</i>	<i>14.1</i>	<i>22.2</i>	<i>23.9</i>
Avg. Indoor Temp Yr. 1	23.6	23.5	23.5	22.4	21.0	21.0	20.9	20.9	21.0	21.2	22.9	23.3
Avg. Indoor Temp Yr. 2	<i>22.6</i>	<i>22.6</i>	<i>22.8</i>	<i>22.3</i>	<i>21.4</i>	<i>21.2</i>	<i>21.1</i>	<i>21.0</i>	<i>20.9</i>	<i>21.0</i>	<i>22.5</i>	<i>22.6</i>
Degree Heating Days Yr.1	0.0	0.0	30.7	218.8	610.0	773.5	1107.3	873.3	792.6	301.0	45.9	0
Degree Heating Days Yr.2	<i>0.0</i>	<i>0.0</i>	<i>2.2</i>	<i>136.2</i>	<i>217.1</i>	<i>262.3</i>	<i>536.9</i>	<i>603.4</i>	<i>412.6</i>	<i>131.7</i>	<i>15.0</i>	<i>9.7</i>
Degree Cooling Days Yr. 1	924.9	682.5	580.5	325.0	61.4	39.1	0.0	0.0	22.8	196.3	542.1	785.4
Degree Cooling Days Yr. 2	<i>492.7</i>	<i>474.9</i>	<i>378.3</i>	<i>109.2</i>	<i>71.2</i>	<i>55.4</i>	<i>0.0</i>	<i>0.0</i>	<i>7.0</i>	<i>135.0</i>	<i>378.4</i>	<i>417.2</i>
<u>Operating Times</u>												
Heat Run Time (hr)Yr. 1	0.0	0.0	0.0	14.9	181.5	314.1	460.9	370.7	305.1	10.2	0.0	0.0
Heat Run Time (hr) Yr. 2	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>6.1</i>	<i>41.1</i>	<i>79.3</i>	<i>469.9</i>	<i>535.2</i>	<i>321.9</i>	<i>37.8</i>	<i>0.0</i>	<i>0.0</i>
Cool Run Time ^d (hr) Yr. 1	492.1	347.2	256.3	81.2	17.5	0.0	0.0	0.0	0.0	52.6	133.8	395.6
Cool Run Time ^d (hr)Yr. 2	<i>431.4</i>	<i>396.4</i>	<i>302.9</i>	<i>23.0</i>	<i>7.4</i>	<i>7.4</i>	<i>0.0</i>	<i>0.0</i>	<i>0.0</i>	<i>10.0</i>	<i>263.2</i>	<i>338.8</i>
Dehumid Mode (hr) Yr. 1	164.9	143.8	70.0	38.0	17.5	0.1	0.0	0.0	0.0	0.0	13.8	133.2

Month	Jul	Aug ^a	Sep	Oct ^b	Nov	Dec	Jan ^b	Feb	Mar	Apr	May	Jun
<i>WH Dehumid (hr) Yr. 2</i>	178.7	126.5	104.2	121.7	52.6	66.3	0.0	0.0	0.0	0.0	0.1	126.3
<u>COP's and Efficiencies</u>												
Heating Mode (-) Yr. 1	0.00	0.00	0.00	1.68	2.10	2.32	1.72	2.17	2.19	2.23	0.00	0.00
Heating Mode (-) Yr. 2	0.00	0.00	0.00	1.31	2.26	2.64	2.28	2.14	2.43	2.13	0.00	0.00
Cooling Mode (-) Yr. 1	3.03	2.89	2.71	2.15	0.11	0.00	0.00	0.00	0.00	4.90	3.39	3.05
Cooling Mode (-) Yr. 2	4.53	4.47	4.49	3.49	3.93	4.14	0.00	0.00	0.00	2.85	3.76	4.46
COP1 (Dehumid) ^c Yr. 1	0.93	0.89	0.91	0.76	0.20	0.48	-	-	-	-	0.71	0.84
Dehumid (l/kWh) Yr. 1	1.35	1.30	1.20	1.10	0.29	0.70	-	-	-	-	1.04	1.23
Dehumid (l/kWh) Yr. 2	1.12	1.11	1.10	1.06	1.04	1.08	-	-	-	-	0.13	1.10

^aMissing data Aug 2 through Aug 6, 2013

^bMissing data Oct 20 through Oct 22, 2015 and Jan 26, 2016

^cHeat pump thermal load includes electric resistance heat.

^dCooling run time includes the time the unit operated in the dehumidification mode.

^eDehumidification COP equals the average of the daily dehumidification COP values (total latent energy divided by electrical energy during active dehumidification)