New York State Energy Research and Development Authority

Measured Performance of Four Passive Houses on Three Sites in New York State

Final Report

November 2014

Report Number 14-44

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Measured Performance of Four Passive Houses on Three Sites in New York State

Final Report

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NYSERDA Report 14-44 NYSERDA Contract 17587 November 2014

Notice

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Acronyms and Abbreviations List

ACH50	Air Change per Hour at 50 Pascal
Btu	British thermal units
COP	Coefficient of Performance
DHW	Domestic Hot Water
EER	Energy Efficiency Ratio
ERV	Energy Recovery Ventilation
HP	Heat Pump
HRV	Heat Recovery Ventilation
kWh	kilowatt-hour
MSHP	Mini-Split Heat Pump
PHPP	Passive House Planning Package
RH	Relative Humidity
SHRV	Sensible Heat Ratio Value
THRV-TOA	Total heat recovered value-total operation annual

1 Introduction

This report summarizes the results of long-term monitoring of four homes on three sites in New York State built to Passive House standards. The homes were all completed since 2010 and detailed monitoring was conducted for at least one year on all homes. Monitoring included tracking and recording of most systems in the homes including heating, cooling, domestic hot water, ventilation, and total house power. Indoor space temperatures and humidity were tracked to assess occupant comfort, and the residents were interviewed to obtain their subjective views of living in the homes and to corroborate observations of the data. The actual energy used in the homes and in selected subsystems is compared to predictions from simulations (Passive House Planning Package and Residential Energy Model (REM/Rate). In addition, efficiency calculations are made from measurements of heating and cooling system inputs and outputs for two ductless heat pumps and for one gas fired combination space and water heating system.

1.1 Background

The term Passive House (Passivhaus in German) refers to a rigorous, voluntary standard for building energy efficiency. It is possibly the strictest building energy standard in widespread use, resulting in little energy used for space heating or cooling. Passive Houses typically have extremely high levels of insulation, very airtight enclosures, highly efficient heat recovery ventilation systems, and strict attention to avoiding thermal bridging. A home built to the Passive House standard will not require more than 15 kWh/m^2 to heat or cool over the course of a year (independent of climate). Also, total energy consumption must not exceed 120 kilowatt-hour per square meters per year ($kWh/m^2/yr$). A list of requirements is provided in Table 1.

Table 1. Passive House Requirements

Area	Requirement for all climates
Annual Space Heating Energy Load	Not to exceed 15 kWh per square meter of net living space per year (4.75 kBtu/sf-yr) or 10 W per square meter peak demand (34 Btu/hr-sf-yr).
Annual Space Cooling Energy Load	In climates where active cooling is needed, the requirement roughly matches the space heating energy demand requirements, with a small additional allowance for dehumidification
Annual Primary Energy Consumption	Total energy (heating, cooling, hot water, lighting, appliances, etc.) must not exceed 120 kWh per square meter of net living space per year (38 kBtu/sf-yr).
Airtightness	Maximum of 0.6 air changes per hour at 50 Pascals pressure (ACH50), in both pressurization and depressurization.
Thermal Comfort	Must be met for all living areas during winter and summer, with not more than 10% of hours per year over 25 °C (~77 °F).

These requirements generally require the following in cold and temperate climates:

- Insulation: Opaque building envelope components should have a heat transfer coefficient (U-value) of no more than 0.15 W/(m²K) (at least R-38).
- Windows: Window frames must be well-insulated and fitted with low-e glazing filled with argon or krypton to prevent heat transfer. This generally means U-value of 0.80 W/(m²K) or less (minimum R-7), with solar heat gain values around 50%.
- Ventilation: Efficient heat recovery ventilation is essential to enable good indoor air quality without energy waste. At least 75% of the heat from the exhaust air must be transferred to the fresh air again by means of a heat exchanger.
- Thermal bridges: All edges, corners, connections, and penetrations must be planned and executed with great care, so that thermal bridges can be avoided or minimized.

Additional quality requirements (soft criteria) also apply to ensure occupant comfort, satisfaction (low equipment noise, ventilation quality, occupant control) and building durability (i.e., no condensation).[1]

In Europe, thousands of Passive Houses have been built and many have been monitored, but the market for these homes in the U.S. is still in its infancy with the first homes having been built within the past five years. In 2011, the first certified Passive House was completed in New York State: the Hudson Passive Project (HPP) in Claverack, NY. Energy engineering, field inspections, testing, and certification of the HPP was conducted by The Levy Partnership with the support of the New York State Energy Research and Development Authority (NYSERDA) High Performance Development Challenge. Subsequent monitoring of the HPP by TLP and CDH Energy determined that home performance exceeded projections. There are now perhaps 50-100 buildings in the U.S. at various stages of Passive Home certification, several of which are in New York State (Passive House Institute US n.d.).

While Passive Houses have been thoroughly studied in Europe, there are fewer examples of monitoring studies in the harsher climate of the northern U.S. where, compared with Europe, both colder winters and hotter, more humid summers pose additional challenges to Passive House designers (Passive House Institute US n.d.). Furthermore, many Passive Houses and other high performance homes in the U.S. are using mini-split heat pumps for point-source heating and cooling, a departure from the common forced air or hydronic distribution systems.

1.2 Objectives

This report describes the performance of four recently constructed Passive Houses in New York State and provides data on mini-split heat pump performance in these homes. Table 2 lists the research questions and how they are addressed in this work.

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1 http://www.passipedia.org/passipedia_en/planning/other_attributs_for_passive_houses?s%5b%5d=soft&s%5b%5d=criteria

Table 2. Research Questions and Approach to Answering Them

Research question	Approach to answering question
What is the energy consumption of these homes by major end-use?	Data collection of equipment power use
How do temperatures fluctuate in these homes (given point-source heating/cooling)?	Indoor temperature data collection at various locations
How are the mini-split ductless heat pumps in these homes performing? What is their effective coefficient of performance?	One-time performance tests and continuous monitoring of power and inlet/outlet temperatures
How does actual performance (in terms of energy use) compare to that predicted (and assumed) by the software modeling?	Comparison of normalized utility bills to Passive House Planning Package (PHPP) and REM/Rate models
How much energy do they save compared to homes built to code minimum?	Comparison of normalized utility bills to REM/Rate models of code-level specs for these homes
How do residents feel about living in these homes: how do they manage Passive House features (such as heat recovery ventilation)? Are they comfortable? Are they aware of the superior indoor air quality when compared to standard home construction?	Interviews with residents
Have any moisture, indoor environmental quality or other problems affected these homes, and if so what are the causes?	Periodic inspections, interviews of residents and indoor relative humidity data collected in various rooms

1.3 Sites

The following houses were included in this effort:

- The Stuyvesant House, Stuyvesant, NY is a 2,500-square-foot, single-family home to be completed in the first quarter of 2013 and occupied by family of four. (Energy and environmental monitoring plus heat pump measurements for one heat pump.)
- Hudson Passive Townhomes, Hudson, NY, built by Columbia County Habitat for Humanity (Figure 1). This is a 3,200-square-foot duplex to be completed in the first quarter of 2013. (Energy and environmental monitoring only.)
- R-House, Syracuse, NY is a 1,200-square-foot, single-family home currently occupied by one person. (Energy and environmental monitoring plus heat pump measurements for one heat pump.)

Table 3 presents characteristics of all three passive houses. Table 4 presents the annuals loads as predicted by the Passive House Planning Package (PHPP) software.

Figure 1. Hudson Passive Townhomes

Table 3. Characteristics of the Homes

	Hudson Passive Townhomes	Stuyvesant House	R-House
Type of building	2-story side-by-side duplex	3-story detached home	2-story detached home
Foundation type	Conditioned basement	Conditioned walk-out basement	Slab on grade
Conditioned area (sf)	3,200	2,500	1,200
Primary wall R-value	43	55	60
Primary roof R-value	87	54	68
Primary slab R-value	56	46	48
Glazing area (sf)	350	390	212
Primary glazing R-value	9	9	7
Heating system	MSHP	MSHP	MSHP + hydronic coil in ventilation air
Cooling system	MSHP (1 per residence)	MSHP (1, (option for 2 more)	MSHP (1)
Ventilation system	HRV	HRV	HRV
DHW heater	Electric tankless	Electric tankless	40-gallon, gas-fired, sealed-combustion

Table 4. Calculated Annual Loads from PHPP

	Hudson Passive Townhomes	Stuyvesant House	R-House
Predicted annual heat demand per sf (kBtu/yr-sf)	4.54	3.58	4.75
Total predicted annual heat demand (kBtu/yr)	14,500	8,950	5,700
Predicted annual total site energy demand per sf (kBtu/yr-sf)	38	36	34
Total predicted annual total site energy demand (kBtu/yr)	121,600	90,000	40,800

2 Technical Approach

Monitoring equipment was installed to measure the performance of all three passive houses. Monitoring included the testing of heat pump coefficient of performance (COP) (in two homes), indoor air temperatures, and relative humidity at various locations, domestic hot water (DHW) use, and various internal loads. Indoor air temperatures at various locations were measured to examine how indoor air temperature varies with outdoor air temperature.

All homes are in Climate Zone 5A. Table 5 and Table 6 present minimum, maximum, and average outdoor air temperatures for each month in 2012 at the closest weather stations to the sites. In 2012, the average annual temperature at the first two sites was 49.7 °F whereas at the third site, the average annual temperature was 51.6 °F.

Table 5. Climate Data of Hudson Passive Townhomes and the Stuyvesant House (2012)

Data were collected from Albany International Airport's weather station (KALB).

	Minimum T (°F)	Maximum T (°F)	Average T (°F)
January	0.0	51.1	29.3
February	9.0	57.9	32.5
March	14.0	80.1	45.1
April	30.0	89.1	48.5
May	37.9	90.0	63.1
June	48.2	93.0	66.7
July	54.0	98.1	74.3
August	51.1	91.0	71.9
September	39.9	84.9	62.1
October	27.0	73.9	54.3
November	21.0	66.0	37.2
December	17.6	55.4	33.8

Table 6. Climate Data for R-House (2012)

Data were collected from Syracuse Hancock International Airport's weather station (KSYR).

	Minimum T (°F)	Maximum T (°F)	Average T (°F)
January	-2.9	55.0	29.8
February	13.1	55.0	32.5
March	14.7	80.1	44.4
April	26.1	89.1	45.5
May	39.9	91.9	63.7
June	46.9	93.9	68.5
July	57.9	99.0	76.1
August	51.1	97.0	72.4
September	39.9	86.0	63.7
October	30.0	75.0	54.0
November	24.1	72.0	38.8
December	10.0	70.0	34.4

2.1 Data Acquisition

The following general approach and monitoring points (Table 7) were used for data acquisition. A detailed list specific to each house is provided in the section on each house.

Air flow measurements: An Energy Conservatory Duct Blaster with a capture hood was used to take one-time measurements of air flow from ductless heat pumps at a variety of fan speeds at the Stuyvesant House and R-House sites. The operating range of the duct blaster is 50-1500 CFM with an accuracy of ±3% of the indicated reading or 1 CFM (whichever is greater). Resolution is 10 CFM. The fan current was correlated to airflow and monitored continuously.

Temperature measurements: Thermistors were used to measure heat pump supply and return air temperatures, indoor air temperatures at various locations, and outdoor air temperature. Data were acquired by a Campbell Scientific data logger (models CR206x, CR800, and CR1000) every 15 seconds.

Relative Humidity (RH) measurements: Vaisala relative humidity (RH) sensors were used to measure supply and return air RH of heat pumps, and indoor air RH at various locations. Data was acquired by a Campbell Scientific data logger (models CR206x, CR800, and CR1000) every 15 seconds.

Current measurements: Heat pump compressor and fan current measured with analog sensors, resistance element status, and vent fan runtime were measured by Veris current switch sensors. Data were acquired by a Campbell Scientific data logger (model CR206x) every 15 seconds.

Power consumption measurements: Total electric power consumed by the heat pumps, DHW heaters; HRVs and total house power were measured by power transducers. Data were acquired by a Campbell Scientific data logger (model CR206x) every 15 seconds.

Table 7. General Monitoring Points

Monitoring point	Purpose
Outdoor air temperature and humidity	Heating load calculations
Space temperatures (multiple)	Distribution of heat throughout the house
Space humidity	Distribution of humidity throughout the house
Heat pumps	Power and runtime of heating and cooling system
Heat pump supply air	Temperature and humidity for heat pump COP calculations
Heat pump return air	Temperature and humidity for heat pump COP calculations
Electric backup heating	Power and runtime of resistance backup heating
HRV	Power and runtime of ventilation system
DHW	Energy used for domestic hot water
Total house power	Plug and other baseload energy use

2.2 Energy Consumption Analysis

Cooling and heating capacities of the heat pumps at Stuyvesant House and R-House were calculated using the following procedures.

To calculate cooling efficiency (EER) of the heat pumps, instantaneous power consumption was logged along with the cooling output of the unit. Temperature and relative humidity data were recorded along with airflow to determine the cooling output. To calculate EER, Equation 1 was used:

$$EER = \frac{TCC}{HPP} \tag{1}$$

where

- HPP = Total power, watts
- TCC = Total cooling capacity, Btu/h is defined by Equation 2

$$TCC = \frac{60 \times CFM \times (h_{return} - h_{supply})}{SPV_{supply} \times (1 + W_{supply})} \tag{2}$$

where

- CFM = Combined volumetric air flow rate at the supply grilles, ft^3/min
- H = Air enthalpy, Btu/lb
- SPV = Specific volume, ft^3/lb
- W = Specific humidity, lb/lb

Likewise, total heating capacity (THC) was calculated using Equation 3:

$$THC = 1.08 \times CFM \times (T_{supply} - T_{return}) \tag{3}$$

The heat pump COP is calculated by Equation 4:

$$COP = \frac{THC}{3.412 \times HPP} \tag{4}$$

Total energy consumption for all three passive houses was measured to determine total electric power of the whole house and selected circuits at each site. This information was used to calculate total energy consumption. Using the sensors previously mentioned, space heating, DHW, and ventilation energy use per year was estimated. Space conditioning energy was normalized with outdoor air temperature and for two projects energy usage was compared to expectation and building code based on computer models.

3 Stuyvesant House

3.1 Introduction

The Stuyvesant House (Figure 2) is a single-family, detached three-bedroom home on three levels totaling 2,583 square feet of floor area. The semi-finished walkout basement level includes a workshop, studio, and large unfinished living space oriented toward the south (Figure 3). The main floor is primarily an open plan living/dining/kitchen area facing south and a master bedroom suite facing north. The living area is a two-story space. The second floor has a large loft overlooking the first floor living area and two bedrooms toward the north with a bathroom in the center of the floor. Open stairs connect all floors. The southern portion of the home is dominated by a large two-story open space and large south-facing windows (Figure 4 and Figure 5). The Stuyvesant House was built with Passive House features as described in Table 8.

Figure 2. Stuyvesant House

Figure 3. Stuyvesant House Plans – Basement, First and Second Floors

Source: BarlisWedlick Architects

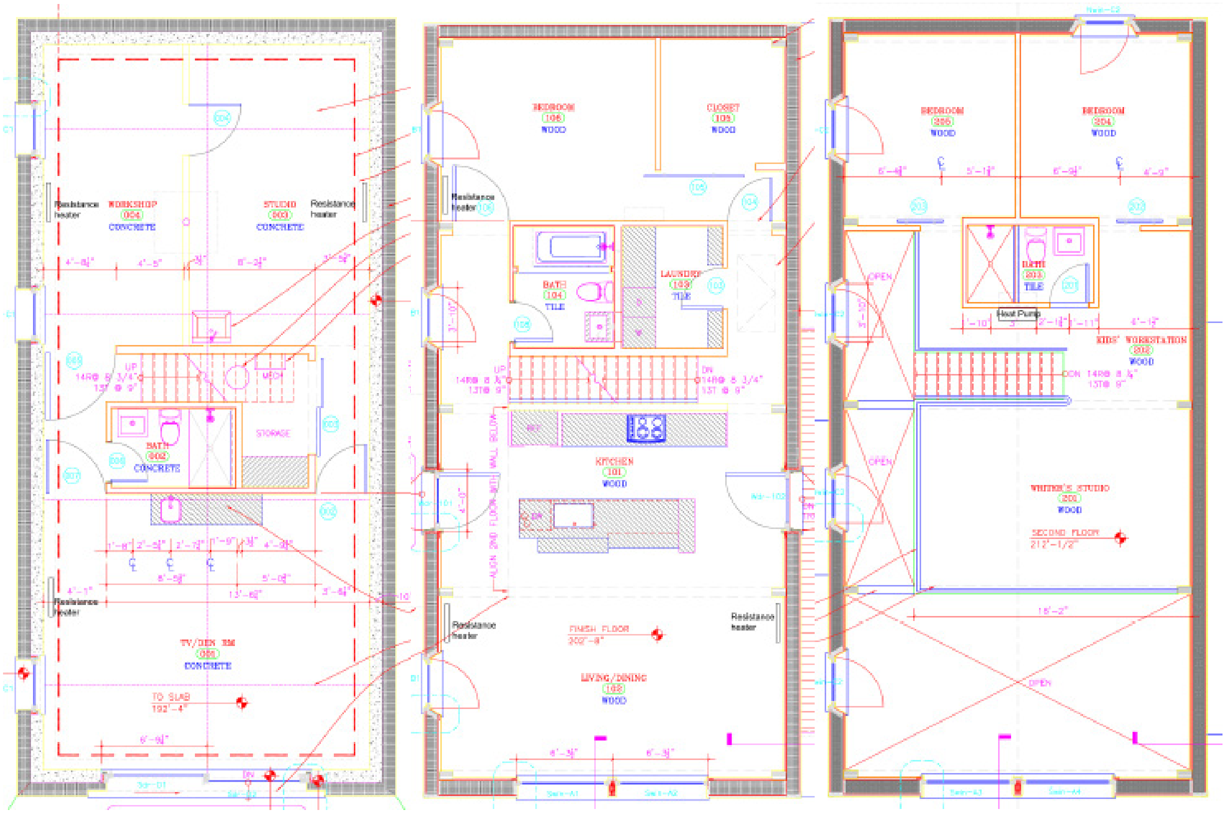


Figure 4. Stuyvesant House Elevations – South

Source: BarlisWedlick Architects

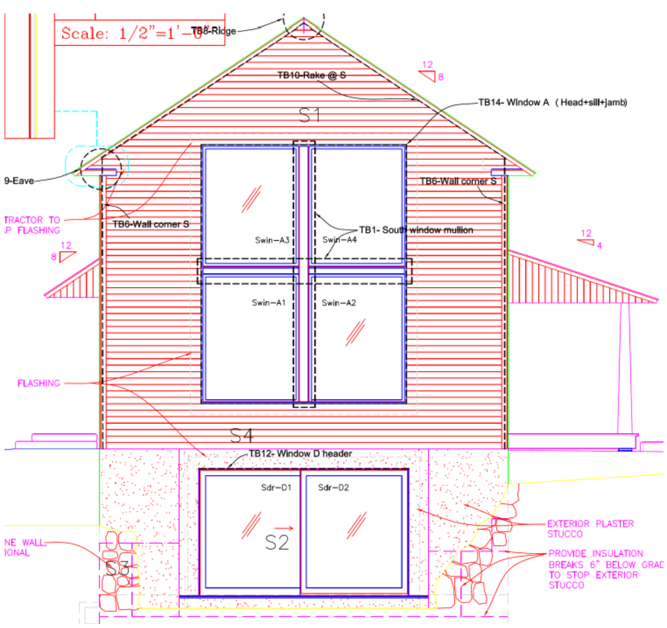


Figure 5. Stuyvesant House Elevations – West

Source: BarlisWedlick Architects

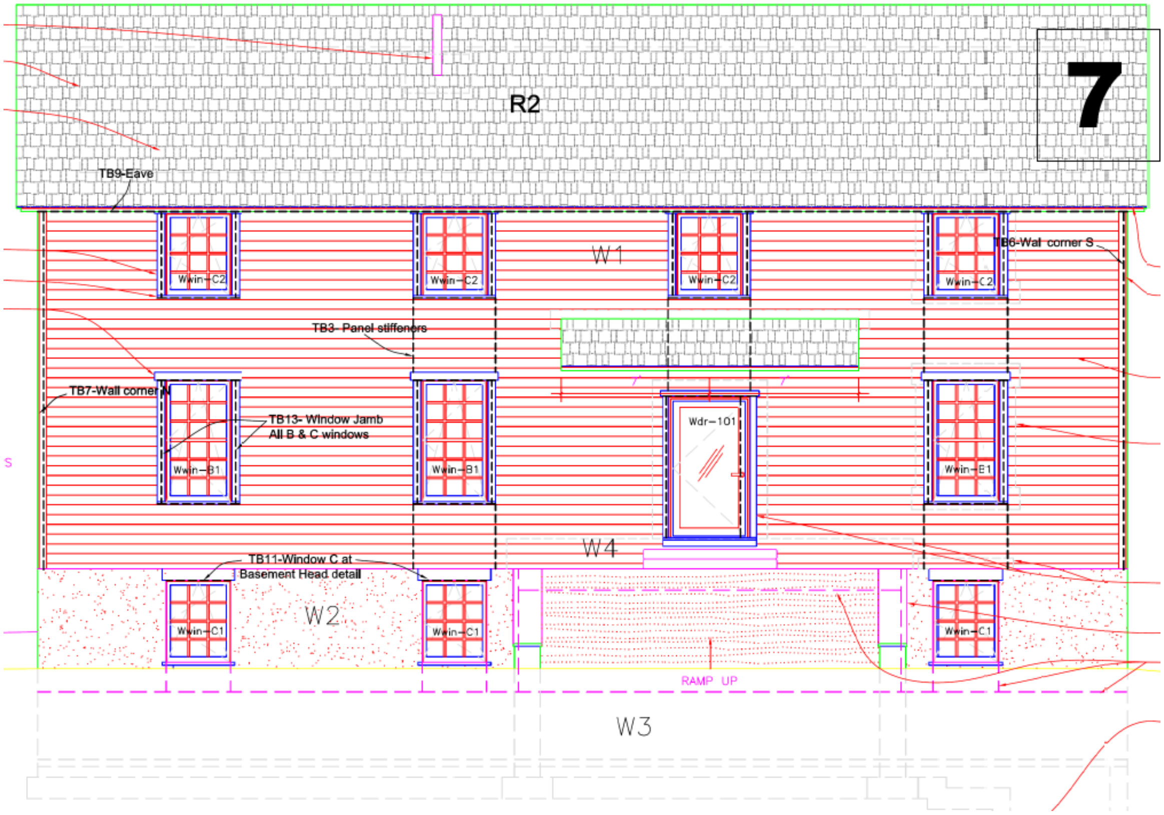


Table 8. Passive Townhome Specifications

Item	Specification
Slab	R-46 under slab insulation
Foundation wall	R-46 Neopor insulation
Exterior walls	R-55 Neopor EPS SIPs
Roof	R-54 Neopor EPS SIPs
Windows and doors	Intus triple pane overall U-factor 0.15; SHGC 0.62
Infiltration	0.22 ACH50
Heating/cooling system	¾ ton Fujitsu-MSHP-ASU9RLS wall mounted ductless heat pump
Ventilation system	Zehnder ComfoAir 350 HRV
Water heating	Tankless electric

The Stuyvesant House uses a Zehnder ComfoAir 350 Heat Recovery Ventilator (HRV) to pre-condition air coming into the building. The HRV recovers heat from the outgoing air to preheat the incoming air. The heating and cooling loads are met by a ¾-ton Fujitsu-MSHP-ASU9RLS wall mounted ductless heat pump. The single indoor unit is installed in an open area high on the second floor to serve the entire house. Figure 6 shows the equipment.

Figure 6. Stuyvesant House Equipment

Fujitsu wall-mounted heat pump indoor (left), and outdoor (center) units and Zehnder ComfoAir Heat Recovery Ventilator (HRV) (right).

3.2 Monitoring Approach

Campbell Scientific CR206x and CR800 data loggers were installed along with various sensors and meters to measure system performance and energy use. Further details about the monitoring system are provided in this section. The data points collected are shown in Figure 7 and Table 9. They were selected to measure:

- Induced fan current (FC) to estimate the amount of air (CFM) supplied by the heat pump indoor unit using a correlation developed from one-time airflow measurements.
- Inlet and outlet air conditions to and from the heat pump indoor unit (RHR, TARI, TASI4 and RHS) to calculate the enthalpy difference (HAS-HARI) and thus estimate the cooling or heating load of the heat pump (QC,QH).
- Heat pump energy consumption (WHP) to calculate the performance of the heat pump in terms of EER and COP.
- Total house energy consumption (WT) to estimate the portion of energy used by the heat pump.
- TASI1, TASI2 and TASI3 to check the spatial variation of the supply air from the Heat Pump (HP indoor unit.
- Compressor current (CC) to track the relative loading of the compressor.
- Run times for heat pump fan and compressor, and HRV (SF, SC, SHRV) to determine the total operation hours of each component during heating and cooling.

Figure 7. Schematic of Ductless Heat Pump with Data Points

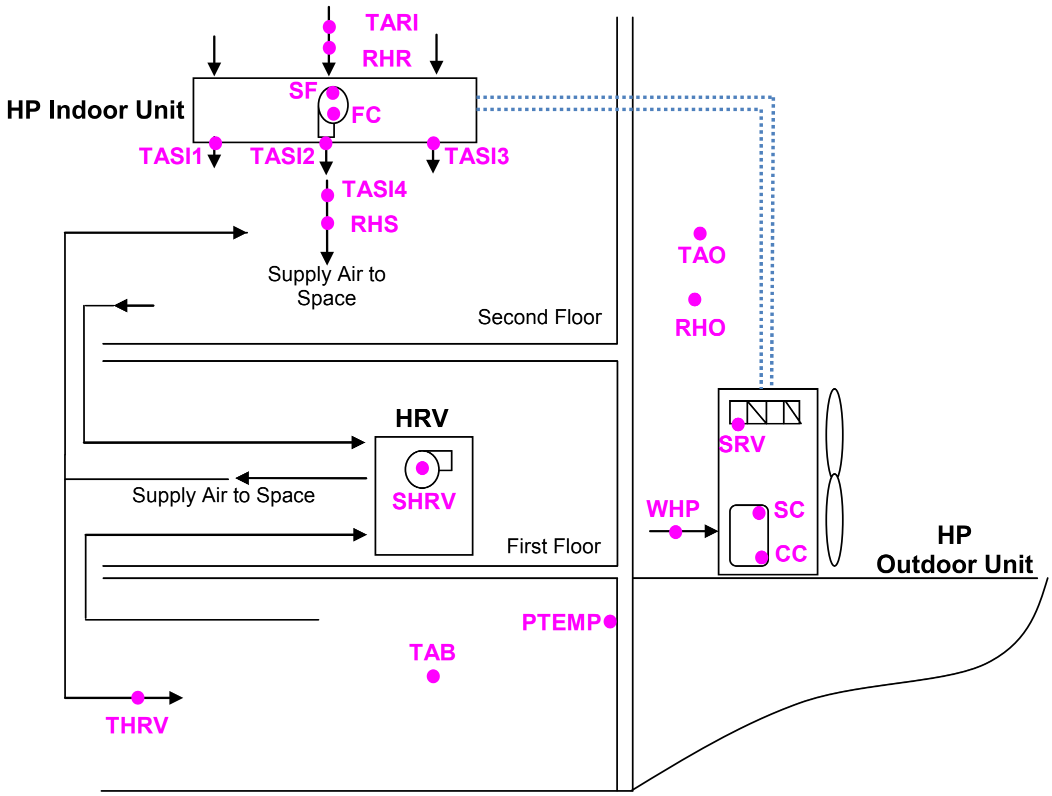


Table 9. Stuyvesant House Data Points

Data Point	Description	Eng Units	Instrument
TAI1	Room air temperature – basement den		Hobo U12-001
TAI2	Room air temperature – first floor office	°F	Hobo U12-001
T/RHAI3	Room air temperature and RH – basement studio	°F / %	Hobo UX100-011
T/RHAI4	Room air temperature and RH – first floor main room	°F / %	Hobo UX100-011
TAI5	Room air temperature – first floor master bedroom	°F	Hobo U12-001
TAI6	Room air temperature – second floor bedroom 2	°F	Hobo U12-001
TAI7	Room air temperature – second floor bedroom 3	°F	Hobo U12-001
TASI1	Supply Air Temperature #1	°F	Minco 10k Type 2
TASI2	Supply Air Temperature #2	°F	Minco 10k Type 2
TASI3	Supply Air Temperature #3	°F	Minco 10k Type 2
TARI	Return Air Temperature	°F	CS215
RHR	Return Air RH	%	CS215
TASI4	Supply Air Temperature 4	°F	CS215

Table 9 continued

Data Point	Description	Eng Units	Instrument
RHS	Supply Air RH	%	CS215
VF	Fan Speed		Monarch
TAO	Outdoor Temperature	°F	CS215
RHO	Outdoor RH	%	CS215
TSL	refrigerant at condenser	°F	Minco 10k Type 2
CC	Current compressor	amps	Veris H721LC (10a)
FC	ID Fan Current	amps	Veris H721LC (10a)
SRV	Status reversing valve	minutes	Senva C-2300
SC	Compressor runtime	minutes	Inferred from CC
SF	Fan Runtime	minutes	Inferred from FC
WHP	Heat Pump Power (20 amps)	kWh	Wattnode WNB-208-Y-P
WDHW	DHW Power (150 amps)	kWh	Wattnode WNB-208-Y-P
WT	Total House Power (200 amps)	kWh	Wattnode WNB-208-Y-P
SHRV	Vent Fan Runtime	minutes	Senva C-2300
THRV	HRV supply temperature	°F	Minco 10k Type 2
TAB	Basement Air Temperature#4	°F	Minco 10k Type 2

Figure 8 shows the monitoring equipment installed at the Stuyvesant House.

Figure 8. Monitoring Equipment at Stuyvesant House

(a) Three temperature sensors measured supply air temperature at three locations and one T/RH sensor at fourth location; (b) Wireless datalogging system for monitoring the performance of the evaporator; (c) MSHP outdoor unit; (d) Hobos to monitor indoor air T/RH at various locations; (e) Dataloggers for data collection

(a) 

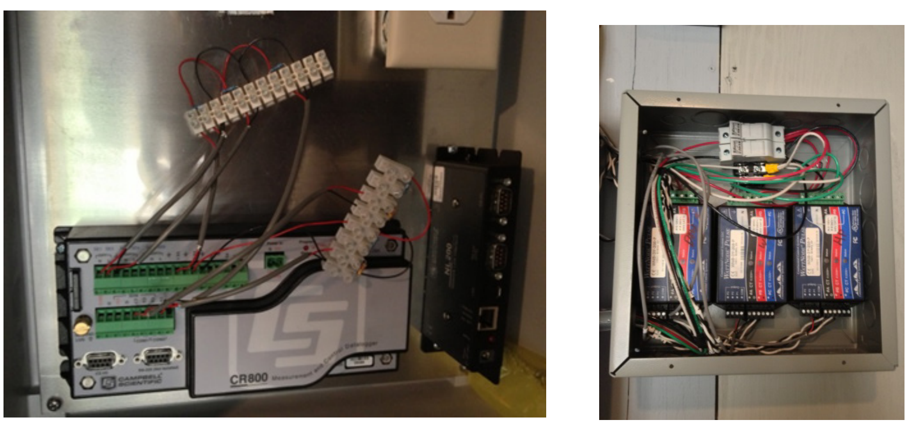
Figure 8 continued

(b)

(c)

(d)

(e)



3.3 Measured Results

3.3.1 Monthly Energy Use and Loads

Table 10 summarizes the total energy consumption as well as energy usage by individual systems and their operation hours over the course of 12 months from June 2013 through May 2014. Most of the variations in electricity are due to seasonal temperature swings. Some data were missed in September and October (Sept. 6-9 and Sept. 13-Oct. 8) due to interruptions in data logger communications. These missing data were adjusted for by extrapolating using the best fit equation for heat pump energy as a function of outdoor air temperature; DHW energy, "other" energy (a component of Total House Energy) and HRV runtime were extrapolated linearly based on the number of hours of missing data in each month.. HP runtime does not include any adjustment for missing data.

Table 10. Monthly Energy Use and Systems Operation Hours for Stuyvesant House

The shaded months are missed data.

Mo nth	Total House Energy (kWh)	HP Energy (kWh)	DHW Energy (kWh)	HP Runtime (hrs)	HRV Runtime (hrs)
Jun-13	899.2	186.3	165.3	639.3	639
Jul-13	1,379.8	447.1	201.1	743.8	717.7
Aug-13	1,149.3	262.7	172.4	744	730.7
Sep-13	1,167.4	188.23	169.6	222.3	604.2
Oct-13	970.6	121.55	325.1	562.8	524.1
Nov-13	1,326.6	195.5	283	720	469
Dec-13	1,991.5	413.3	284.1	744	630.1
Jan-14	2,684.8	525.6	333.6	744	709.5
Feb-14	1,644.3	363.9	288.4	672	662.5
Mar-14	1,657.5	267.3	268.8	744	535.3
Apr-14	1,177.9	108.6	264.7	720	712.8
May-14	1,085.3	136.5	228.7	744	527.4
Total	16,269	3,107.9	2,788.3	8,000.2	7,044.4

3.3.2 Heat Pump Performance

The heat rejected (heating operation) and extracted (cooling operation) from the conditioned space are calculated using the enthalpy difference and air flow according to Equation 5 and Equation 6:

$$Q_c = cfm \times 60 \times 0.075 * (h_{ari} - h_{as})/1000 \quad (5)$$

$$Q_h = cfm \times 60 \times 0.075x\, C_p \times (TASI4 - TARI)/1000 \quad (6)$$

where:

- Qc = Cooling load (MBtu/h)
- Qh = Heating load (MBtu/h)
- cfm = Supply air flow (cfm)
- hari = Return air enthalpy (Btu/lb), hari = f(TARI,RHR)
- has = Supply air enthalpy (Btu/lb), has = f(TASI4,RHS)
- TARI = Return air temperature (°F)
- TASI4 = Supply air temperature (°F)
- Cp = Specific heat of air (Btu/lb °F), 0.24 at STP

Heat pump supply airflow was measured in a series of one-time tests and correlated to fan current. The fan current was monitored continuously and this correlation was used to estimate the flow for each interval. Figure 9 shows the correlation used and quadratic function that provides the best fit to the data.

Figure 9. Air Flow vs. Fan Current for HP Indoor Unit at Stuyvesant House

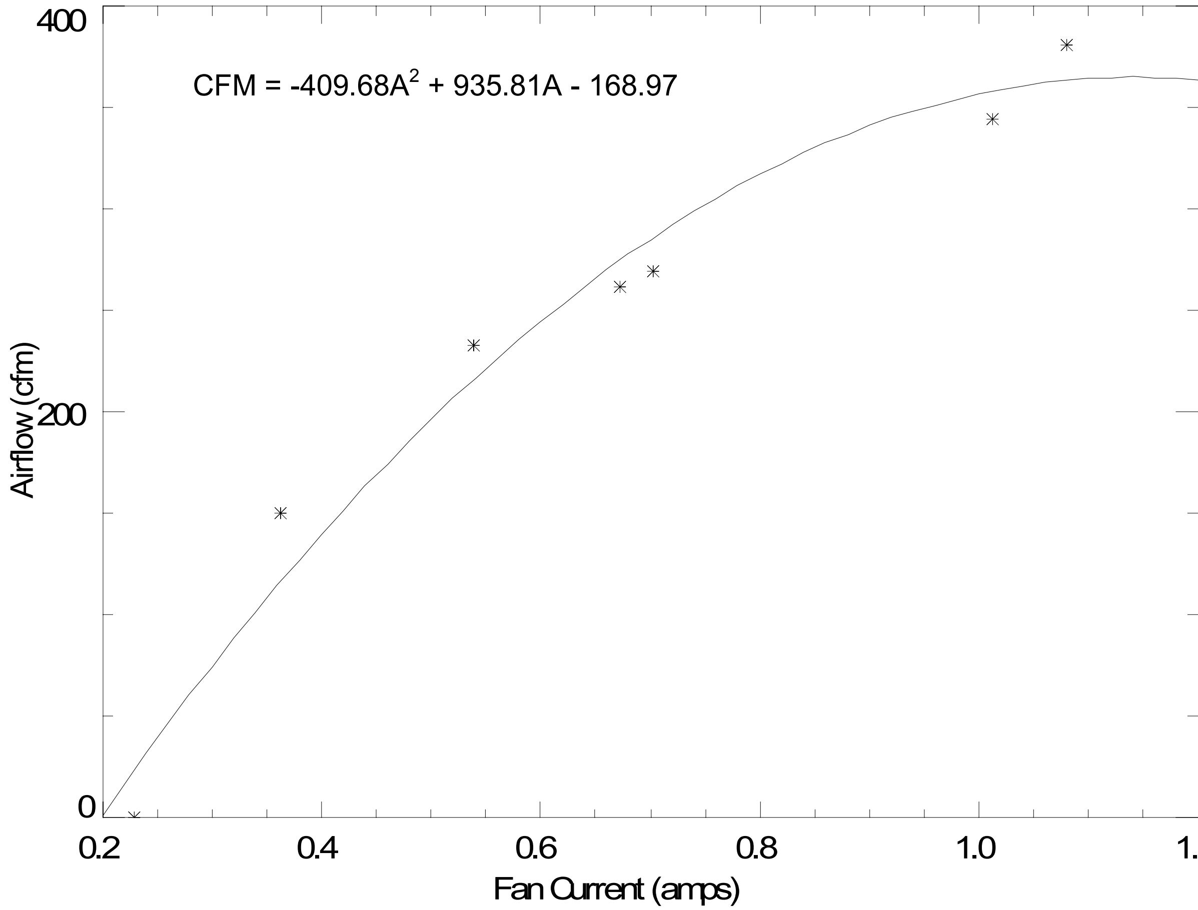


Table 11 summarizes the energy usage, performance, and heating/cooling load of the heat pump. The efficiency of the heat pump during heating is represented by the Coefficient of Performance (COPh). It is calculated as according to Equation 7:

$$COP_h = \ Q_{t,h}\,/(\ WC3\ x\ 4\ x\ 3.413) \qquad (7)$$

where:

- Q t,h = Heat pump heating load (MBtu/h)
- WC3 = Heat pump power consumption (kW)

The efficiency of the heat pump during cooling is represented by the Energy Efficiency Ratio (EERc) and it is calculated with Equation 8:

$$EER_c = Q_{t,c} /(WC3 \ x \ 4) \quad (8)$$

where

- Q t,c = Heat pump cooling load (MBtu/h)
- WC3 = Heat pump power consumption (kW)

Table 11. Stuyvesant House Monthly Heat Pump Energy Use, Heating/Cooling Loads and Performance Data

The shaded rows are months where there were missed data; the heat pump heating runtime and energy includes defrost operation; average ambient temperature for Sept and Oct is from Albany, NY Airport weather station; loads and runtime do not include adjustments for missing data; COP and EER are calculated without including periods of missing data.

		Heating				Cooling			
Month	Ambient Temp. (°F)	Runtime (hrs)	Load (MBtu)	HP Energy (kWh)	COP	Runtime (hrs)	Load (MBtu)	HP Energy (kWh)	EER (Btu/Wh)
Jun-13	67.1	9.8	34.1	3.2	3.2	513.8	3516.8	181.9	19.3
Jul-13	75.6	-	-	-	-	726.0	7123.1	446.9	15.9
Aug-13	69.5	-	-	-	-	695.2	6814.4	262.3	26.0
Sep-13	61.6	-	-	4.1	-	208.3	3525.6	184.0	30.6
Oct-13	52.8	175.4	354.2	52.6	2.0	141.8	434.8	67.7	13.6
Nov-13	38.0	497.9	1339.3	193.5	2.0	-	-	-	-
Dec-13	28.2	697.3	3131.6	413.2	2.2	-	-	-	-
Jan-14	20.7	750.3	3459.7	525.6	1.9	-	-	-	-
Feb-14	22.7	608.7	2153.0	363.2	1.7	-	-	-	-
Mar-14	28.4	611.1	1254.0	266.8	1.4	-	-	-	-
Apr-14	47.6	209.9	282.8	70.0	1.2	154.0	452.6	35.3	12.8
May-14	60.1	45.7	39.1	15.7	0.7	409.2	1606.2	119.0	13.5
Total		3,606.0	12,047.9	1,907.8	1.9	2,848.3	23,499.5	1,297.2	19.7

Table 12 shows the energy used by the heat pump for defrost operation for the entire year.

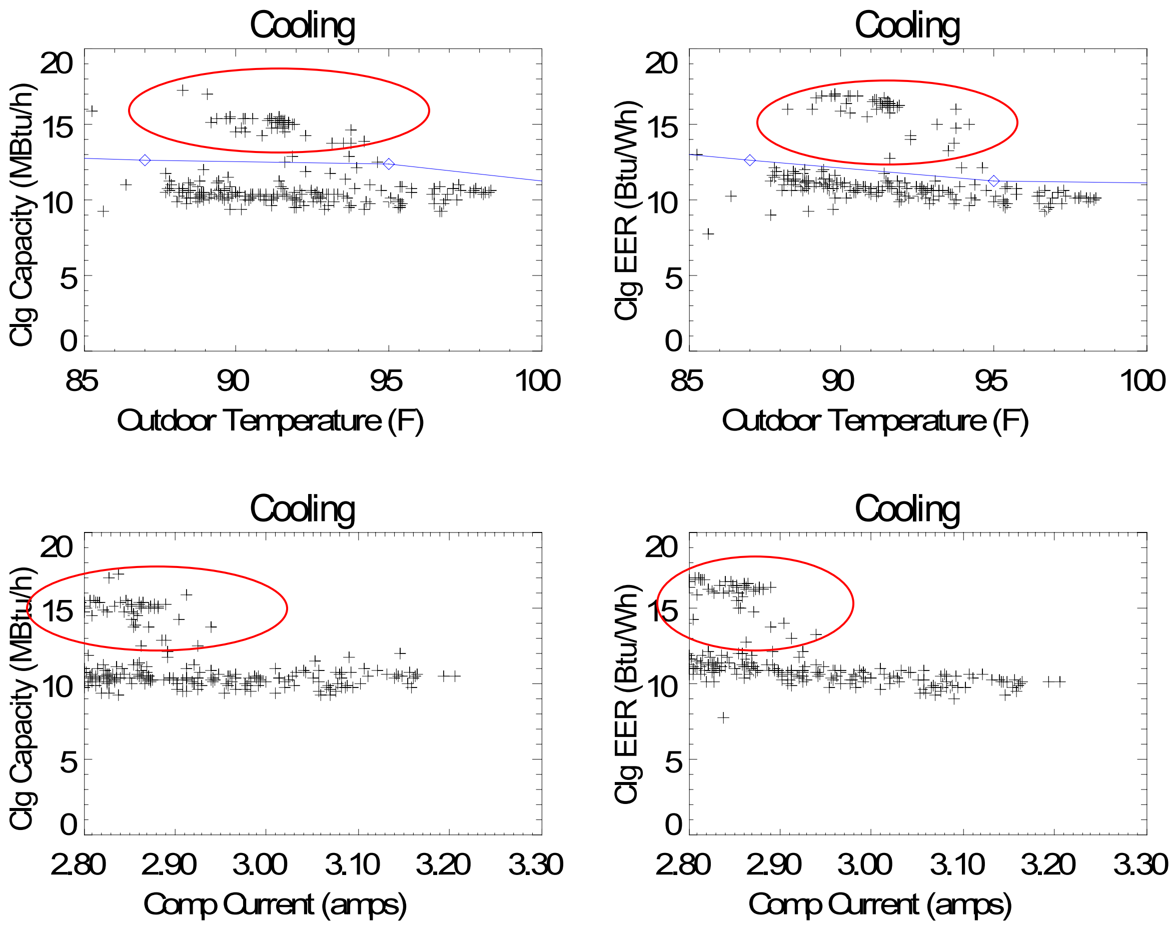
Table 12. Heat Pump Defrost Operation at Stuyvesant House

Month	Ambient Temp. (°F)	Runtime (hrs)	Load (MBtu)	HP Energy (kWh)
Jan-14	20.7	1.6	0.7	1.4
Feb-14	22.7	6.3	25.4	2.2
Mar-14	28.4	0.2	0.0	0.1
Total		8.2	26.1	3.7

Winkler (Winkler 2011) conducted laboratory measurements of the COP and EER of the Fujitsu 12RLS heat pump, a model similar to the 9RLS used at the Stuyvesant House (capacity data was proportionally scaled). The following two sets of plots include comparisons of Winkler's data in cooling (blue points in Figure 10) and heating (red points in Figure 11) with the steady state performance of the heat pump at the Stuyvesant House. The plots demonstrate that the lab and field data are generally in accordance with the exception of the cooling data. The cooling capacity significantly exceeds the nominal rating of 9 MBtu/h.

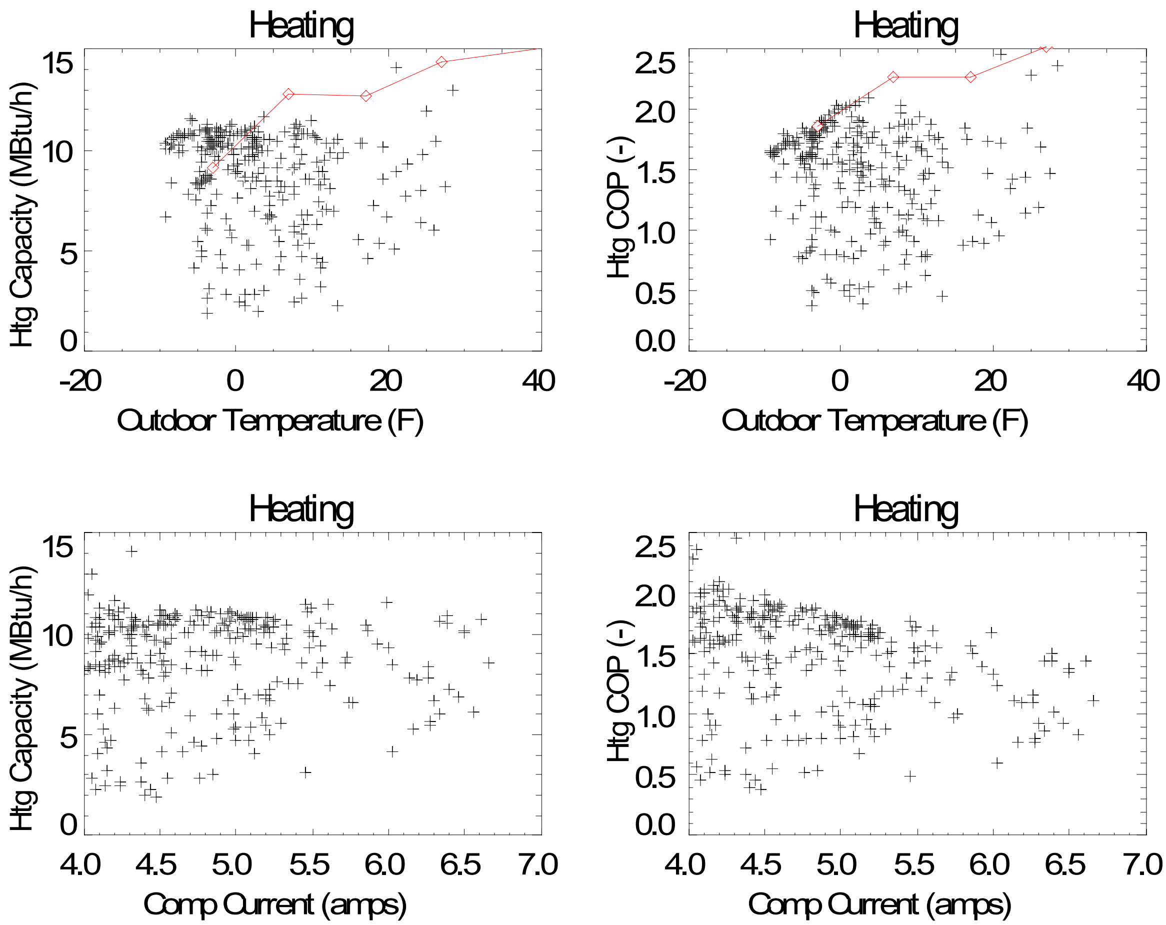
Note that the data points above the blue line (circled) correspond to wet coil operation where the unit goes into a dehumidification mode with lower airflow and colder supply temperatures. At these conditions, the correlation for predicting airflow from fan current no longer works and the predicted cfm is much higher than the actual value. As a result, both the cooling capacity and EER are much higher than expected based on the blue trend. Therefore, the EER in Table 11 is a slight overestimate as is the upper bounds of the capacity listed in Figure 10.

Figure 10. Steady State Heat Pump Performance Compared to Winkler Data for 12RLS (Blue) for Stuyvesant House



		DB (F)	WB (F)	Cooling Capacity (Btu/h)	SHR	Indoor Fan Power	Outdoor Unit Power	COP	Airflow (cfm)	TAS (F)
C-SS-110-H-MX	110	79.8	65.5	12,291	0.89	39	1,057	3.29	475	57.5
C-SS-095-H-MX	95	80	65.7	16,424	0.77	38.4	1,408	3.33	475	53.9
C-SS-087-H-MX	87	79	65.3	16,837	1	38.4	1,296	3.7	475	53
C-SS-082-H-MX	82	78.7	65	17,448	0.74	39	1,220	4.06	472	52.1
C-SS-067-H-MX	67	79	65	18,107	1	38	1,026	4.98	473	52

Figure 11. Steady State Heat Pump Performance Compared to Winkler Data for 12RLS (Red) for Stuyvesant House



	Outdoor	Indoor Temp (F)	Heat Capacity (Btu/h)	Indoor Pwr (W)	Outdoor Pwr (W)	COP	Indr Flow rate (cfm)	Supply Air (F)
H-SS-62-H-MX	62	68.9	22,571	34	1,760	3.69	418	123.3
H-SS-47-H-MX	47	68.4	20,600	34.6	1,893	3.13	413	119.5
H-SS-27-H-MX	27	69	19,132	34	2,163	2.53	450	112.6
H-SS-17-H-MX	17	68.8	16,939	32.5	2,159	2.27	416	110.7
H-SS-7-H-MX	7	69.4	17,110	22	2,166	2.27	452	107.4
H-SS-n3-H-MX	-3	70.1	12,214	14.6	1,915	1.87	416	97.3

3.3.3 Space Heating and Cooling Trends

Figure 12 shows the calculated heat pump load for the monitoring period. During the cooling season, the average cooling load was around 8 MBtu/h. Figure 12 shows cooling peaks of 19 MBtu/h, however this is an artifact of wet coil operation; actual peaks were likely in the 13-14 MBtu/h range, not unreasonable for a unit nominally rated at 9 MBtu/h. Figure 12 shows that during the period with missing data in September are October, the unit was most likely in the cooling mode. A relatively small heating load with an average of 3.2 MBtu/h was observed during heating season with peaks reaching 12 MBtu/h. It is evident from these data and Figs. 12 – 16 below that the heat pump was run continuously throughout the year, consistent with the occupants' self-reported behavior. The occupants appear to have rarely or never turned off the unit and opened the windows.

Figure 12. Stuyvesant House Heating and Cooling Loads

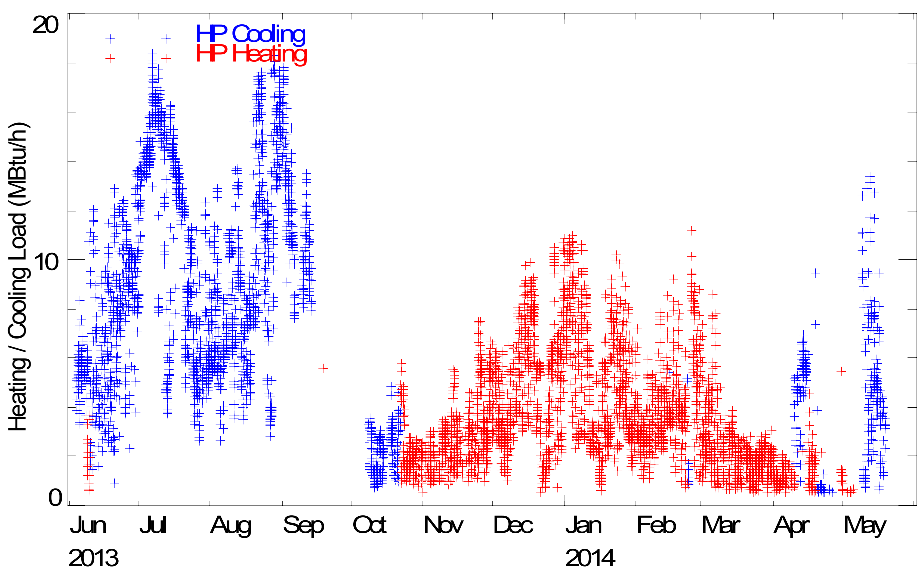
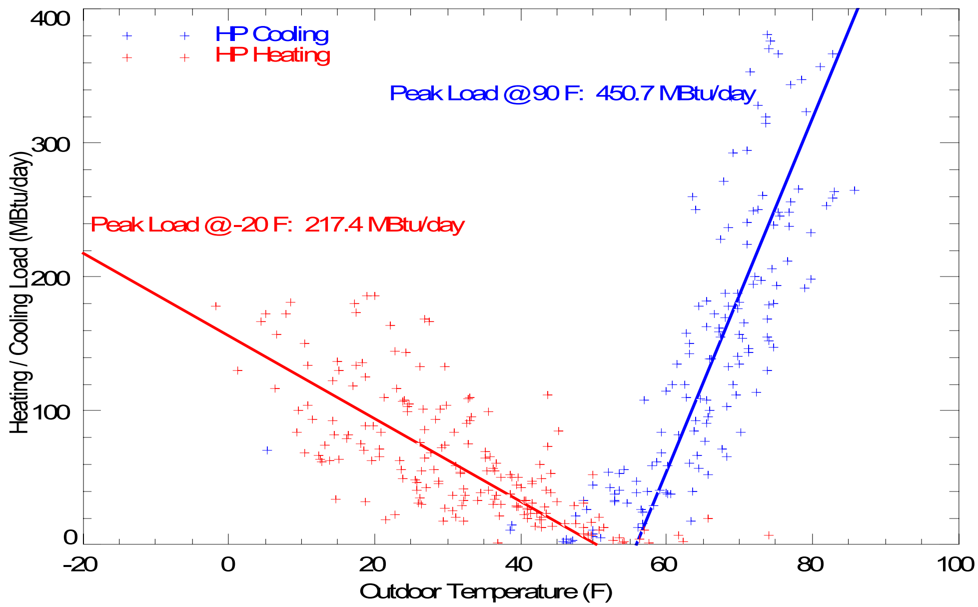


Figure 13 shows the trend of measured space heating and cooling loads with ambient temperature on a daily basis, a trend often referred to as the heating load line. Figure 13 shows that there is a linear relationship between outdoor temperature and heating and cooling loads. It is observed that the cooling load is more sensitive to outdoor temperature change than the heating load and it is predicted to reach 400 MBtu/day at 85 °F while heating load is predicted to reach 219.3 MBtu/day at -20 °F.

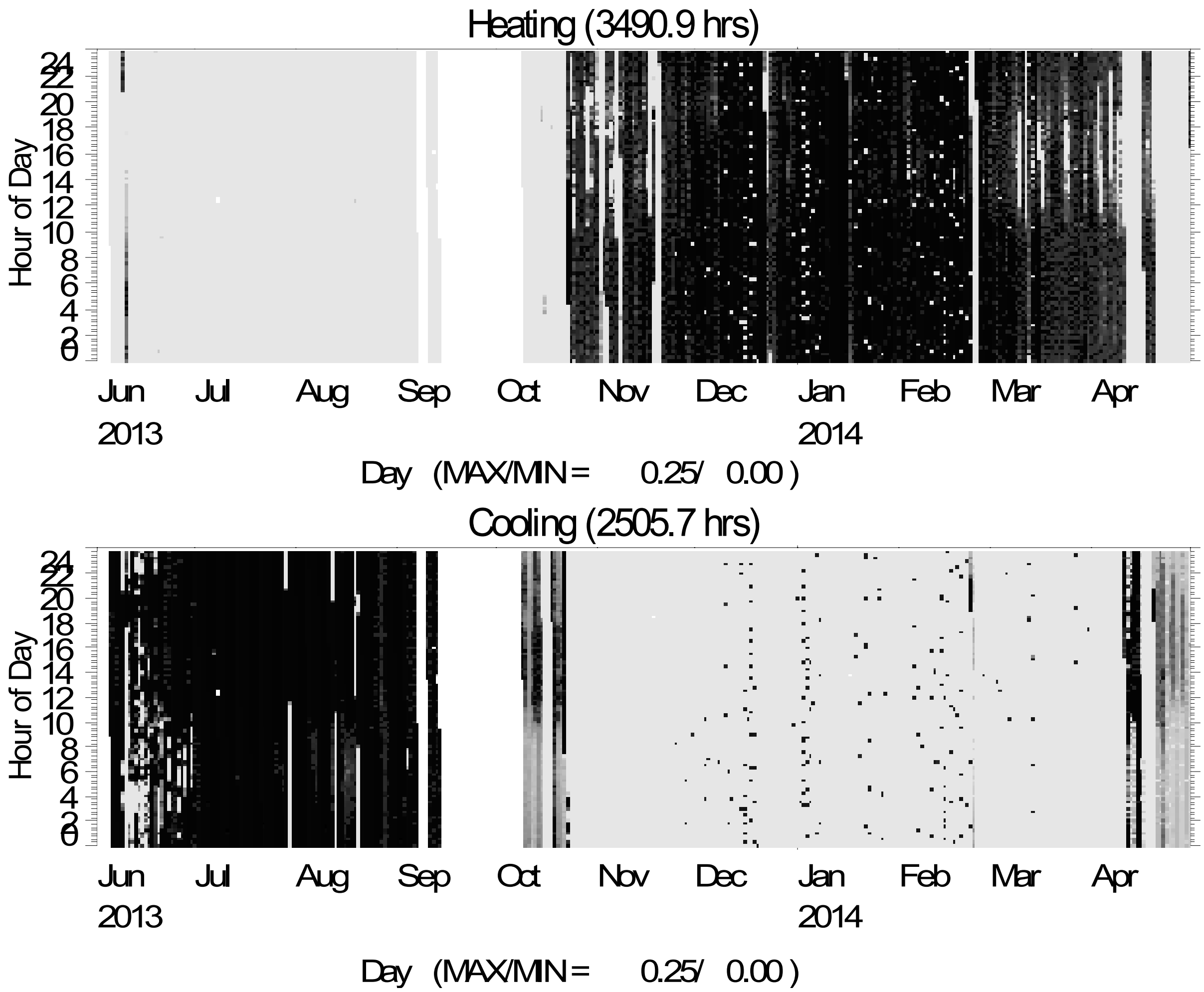
Figure 13. Stuyvesant House Heating and Cooling Loads vs. Outdoor Temperature



The shade plots of runtime displayed in Figure 14 show the operating patterns for heating and cooling operation of the HP. Figure 14 shows the day of the year along the x-axis and the hour of the day on the y-axis. Each day is represented by a vertical stripe of 96 fifteen-minute data records. Heat pump operation in each period is represented by varying shades of gray. Intervals with higher runtime are represented by darker shades of gray, and intervals of lower heat transfers are represented by light shades of gray.

Figure 14 shows that there was a continuous demand for cooling and heating throughout the day (the white area during September and October is where data is missing). The small white dots during heating operation are defrost operation. The heat pump was in heating mode for a 3,491 hrs and in cooling mode for 2,506 hrs.

Figure 14. Stuyvesant House Shade Plots for Heating and Cooling Operations



3.3.4 Indoor Space Conditions and Supply Air Trends

Figure 15 shows the heat pump supply and return air temperatures across the 12-month monitoring period. The average supply temperatures during heating and cooling operation were 92.5 °F and 51.2 °F respectively with peaks of 123 °F and 69.8 °F. The average flow rate during the entire monitoring period (Figure 16) was 147 cfm. The peak flow rate was observed to be around 365 cfm.

Figure 15. Stuyvesant House HP Supply and Return Temperatures Trend

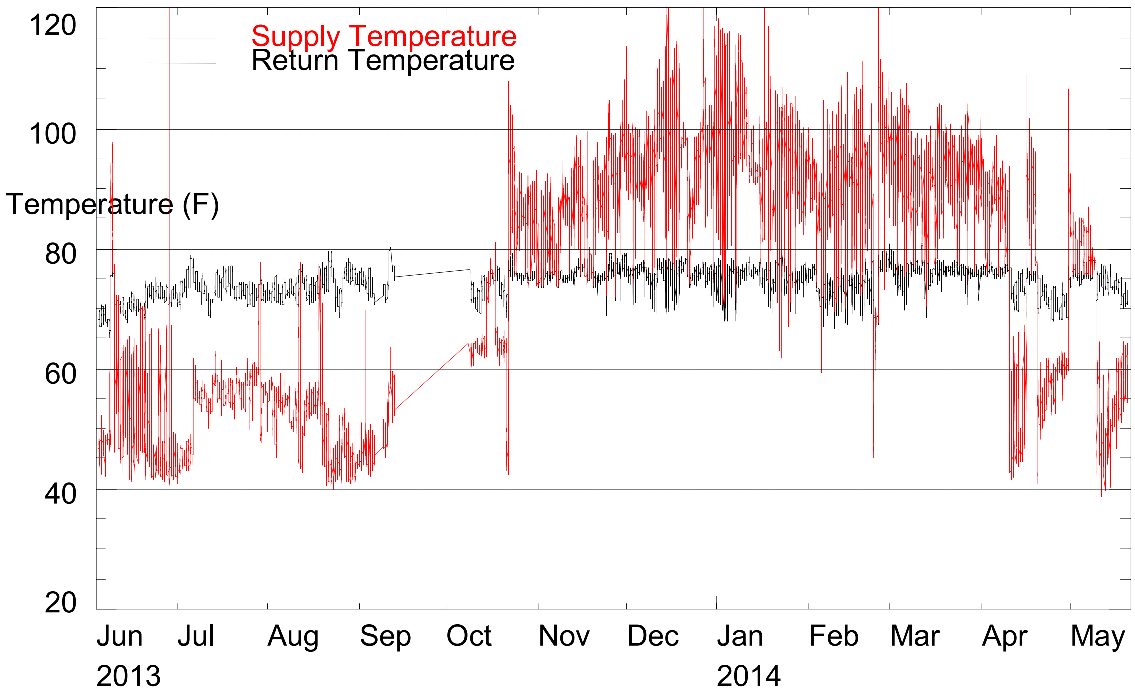
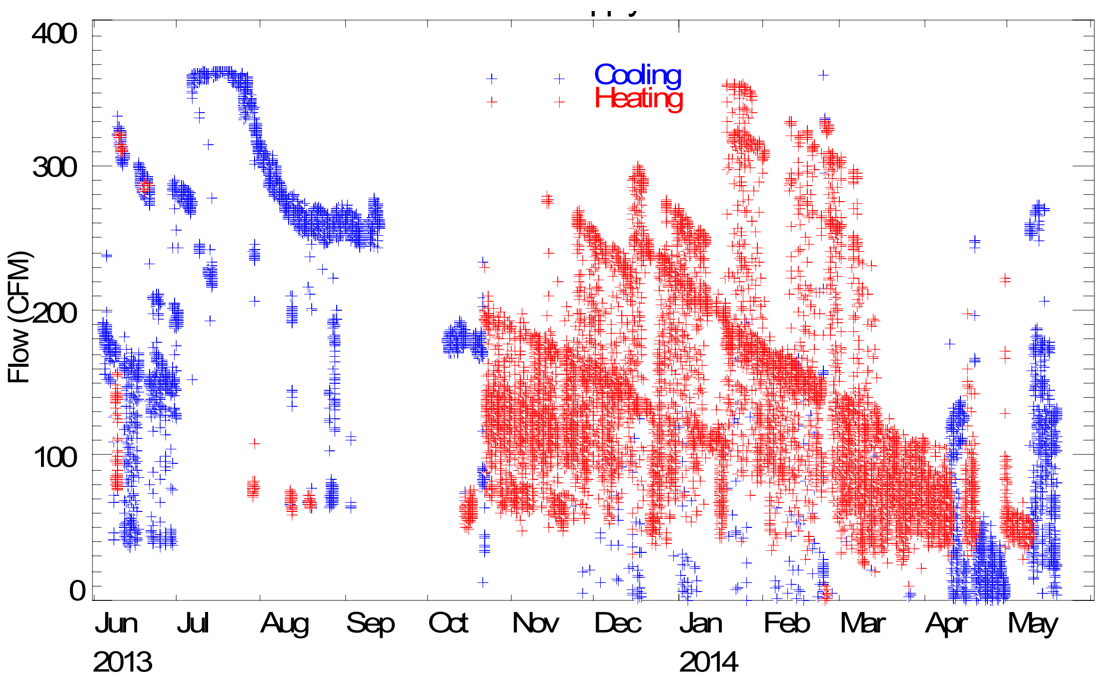


Figure 16. HP Supply Air Flow at Stuyvesant House



3.3.5 Comfort

To help assess comfort criteria, two temperature sensors were placed on each level of the home: the two bedrooms on the second floor, the hall (main living space) and master bedroom on the first floor, and the studio and workshop in the basement.

The temperature spread in the house was analyzed. ACCA Manual J recommends a maximum of 4 °F temperature spread room-to-room (highest minus lowest) (ACCA 1997) at any one time. Using this criteria, the home had a greater than 4 °F spread 58% of the time over the year, however when excluding the basement, the number drops to 5%. Because the MSHP was two floors above the basement and the basement is connected to the rest of the house by a single open staircase, it is expected that it would drift from the rest of the house. The house was plumbed for a second MSHP in the basement, but it was not installed. Temperatures (excluding the basement) varied more in cooling season (7% > 4 °F spread) than during heating season (2% > 4 °F spread) (Table 13). Figure 17 shows these data graphically.

Table 13. Indoor Temperature Spread at Stuyvesant House

	All rooms	All rooms except basement
% time with spread >4°F	58%	5%
% time with spread >4°F heating season	72%	2%
% time with spread >4°F cooling season	43%	7%
Average delta temp (°F)	4.7	2.1
Avg. heating season delta temp (°F)	5.4	1.9
Avg. cooling season delta temp (°F)	4.0	2.4

*N*ote: Heating season defined as October 1 – April 30; cooling season defined as May 1 – September 30.

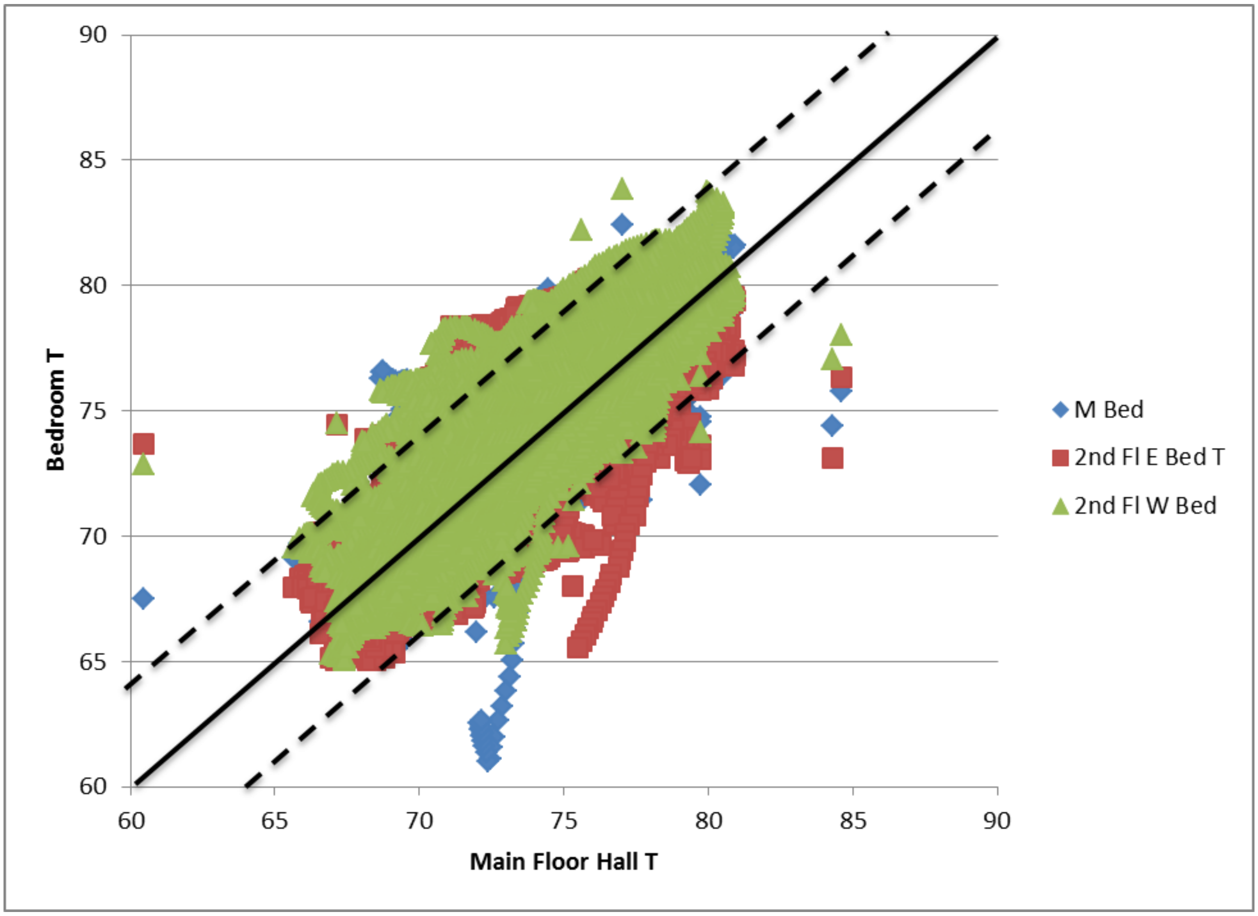
Excluding the basement, the average heating season temperature was 72 °F and the average cooling season temperature was 74 °F. Although the residents did report that the upstairs bedrooms were "stuffy" at times, the average second floor cooling season temperature was only 75 °F and the temperature upstairs was in excess of 78 °F 7% of the time. The maximum temperature reached on the second floor was almost 84 °F. Note that the residents rarely opened windows because of pollen allergies.

During heating season temperatures fell below 68 °F overall 19% of the time, but most of that was in the basement. Excluding the basement, temperatures were below 68 °F 4% of the time. Note that there was some occasional use of resistance heat in the basement studio during the coldest parts of winter.

Table 14. Indoor Temperatures at Stuyvesant House

Temperatures (°F)	All rooms	All rooms except basement	Basement only	2nd floor only
Average temp	72.2	73.2	70.3	73.4
Avg. heating season temp	70.8	72.1	68.2	72.1
Avg. cooling season temp	73.7	74.3	72.4	74.7
Min. heating season temp	70.8	72.1	68.2	72.1
Max. cooling season temp	83.8	83.8	80.6	83.8
% time below 68°F in heating season	19%	4%	49%	4%
% time above 78°F in cooling season	4%	6%	1%	7%

Figure 17. Bedroom vs. Main Floor Hall Temperature Correlation at Stuyvesant House



Another metric of comfort is relative humidity. The humidity control metric used by (Rudd 2013) and others is the number of hours with interior RH levels over 60%. For the first floor, that number was 9% of hours over the year and for the basement studio, that number was 28%. Note that the residents did not express any humidity complaints.

Figure 18 and Figure 19 show heat pump energy use (right vertical axis) along with indoor and outdoor temperatures (left vertical axis) over the heating and cooling season respectively. As expected, heat pump energy increases with decreasing outdoor temperature in heating season and eases with higher outdoor temperature in cooling season.

Figure 18. Heating Season—Heat Pump Power and Temperatures at Stuyvesant House

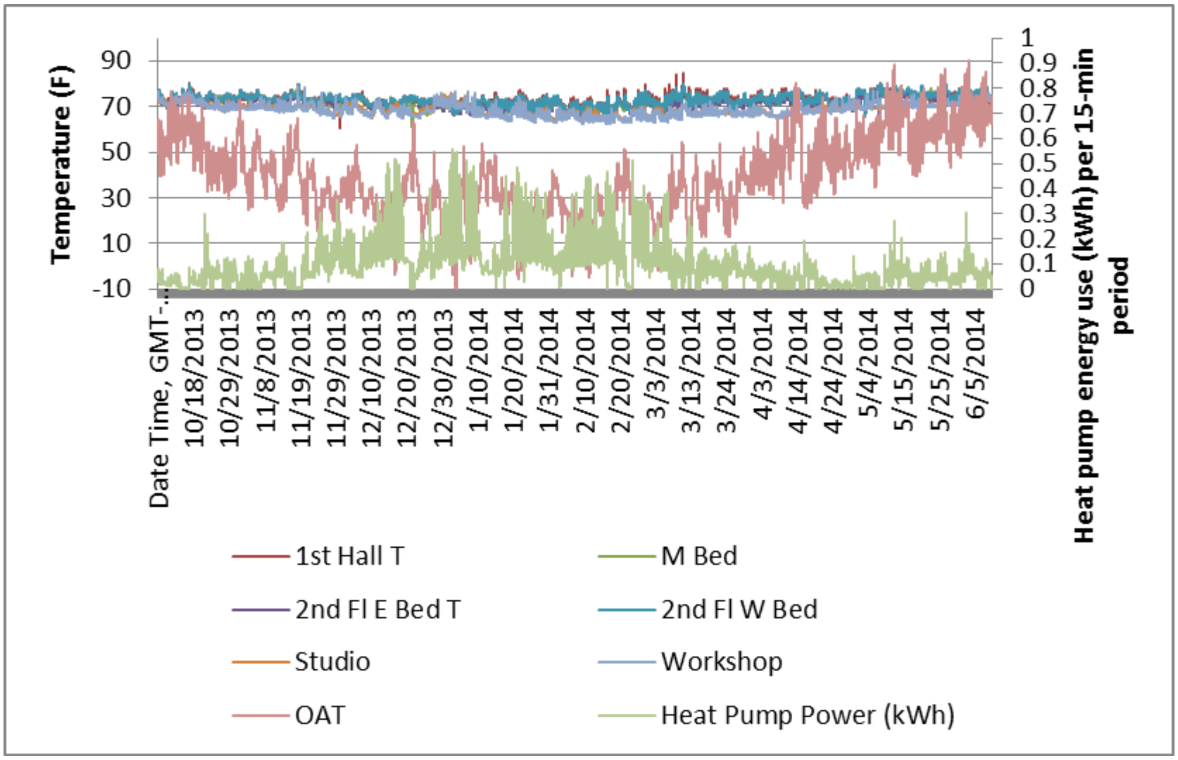
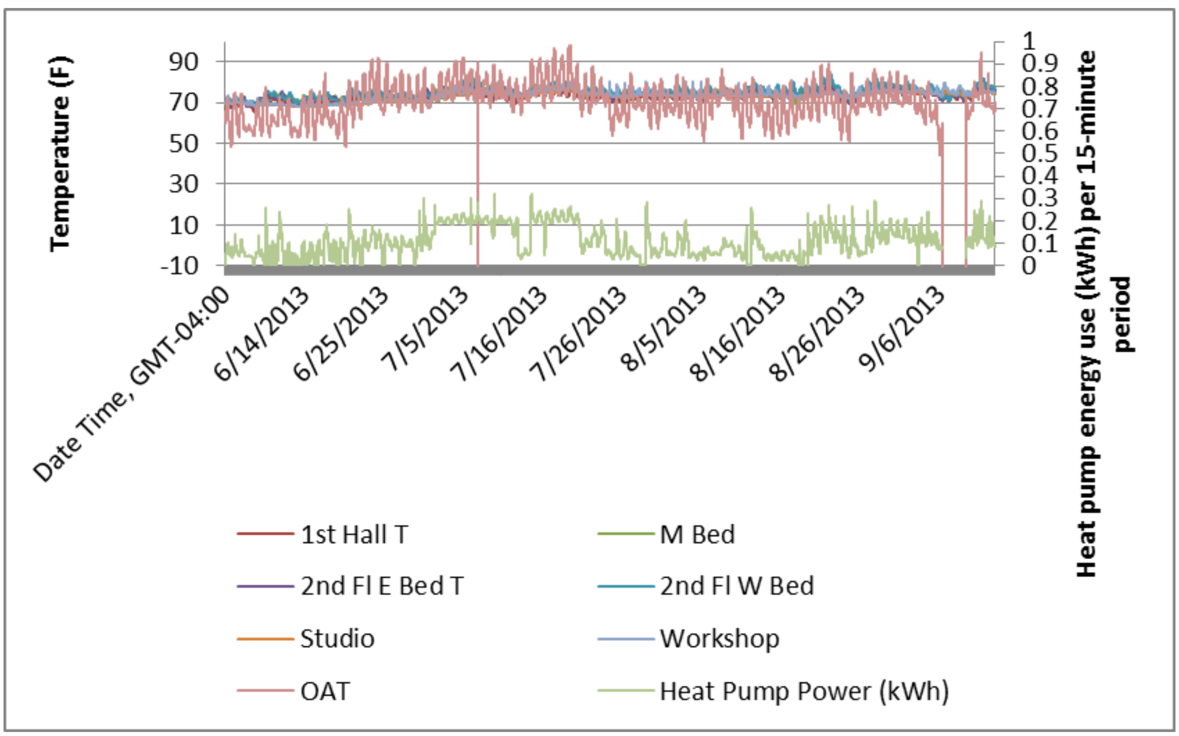


Figure 19. Cooling Season—Heat Pump Power and Temperatures at Stuyvesant House



3.3.6 Electricity Use Trends

Figure 20 shows the variation of the heat pump power over the monitoring period. Figure 20 shows that there was continuous demand for cooling or heating throughout the monitoring period. The plot shows that there was relatively higher power demand during heating than cooling. The power consumption was as high as 2 kW during heating while it only reached 1.1 kW during cooling. Heat pump energy use peaked at 30-35 kWh per day for heating and 20-25 kWh per day for cooling (Figure 21). Average heat pump energy consumption accounts for 24% and 19% of total energy consumption during cooling and heating periods, respectively.

Figure 20. Heat Pump Electric Use at Stuyvesant House

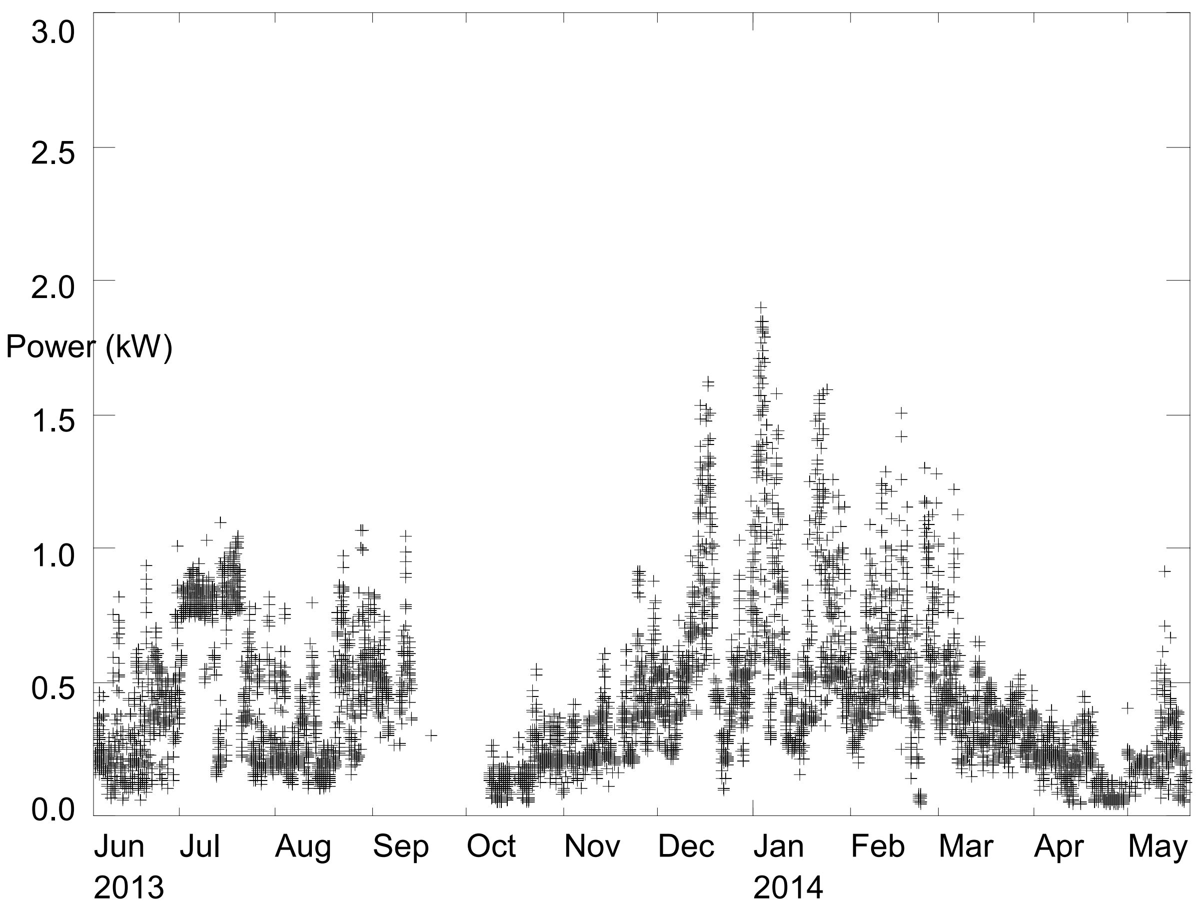
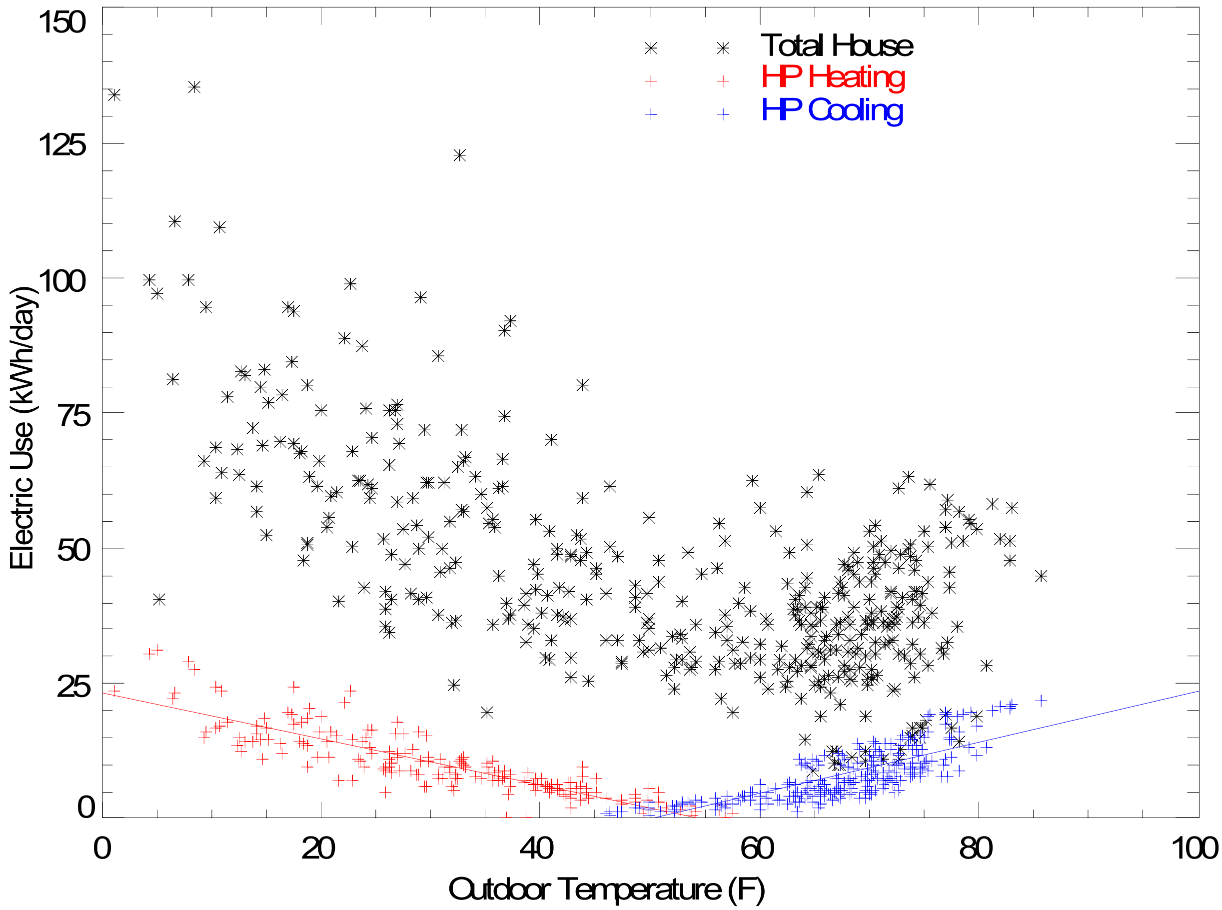


Figure 21. Daily Total and Heat Pump Electric Use vs. Outdoor Temperature for Stuyvesant House



	Coefficients (kWh/day)
Heating	23.369824 + -0.42549768 *T
Cooling	-24.402853 + 0.47919839 * T

3.4 HRV Operation

Figure 22 show the operation trends of the HRV unit. The HRV unit was able to recover a considerable amount of energy (THRV-TOA) during the coldest days of winter. It provides minimal benefit in the summer. The HRV was running for most of the time during the monitoring period (Figure 23).

Figure 22. HRV Unit Operation Trends at Stuyvesant House

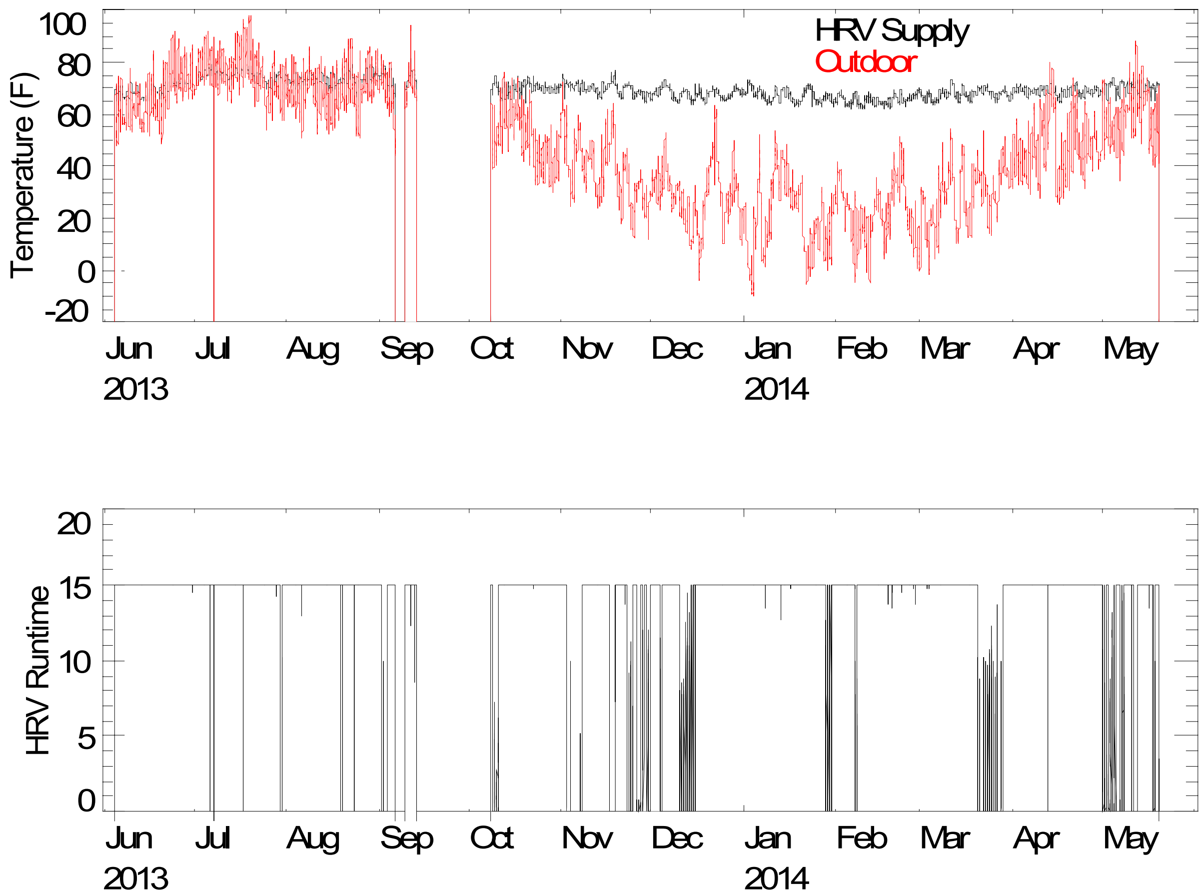


Figure 23. HRV Runtime at Stuyvesant House

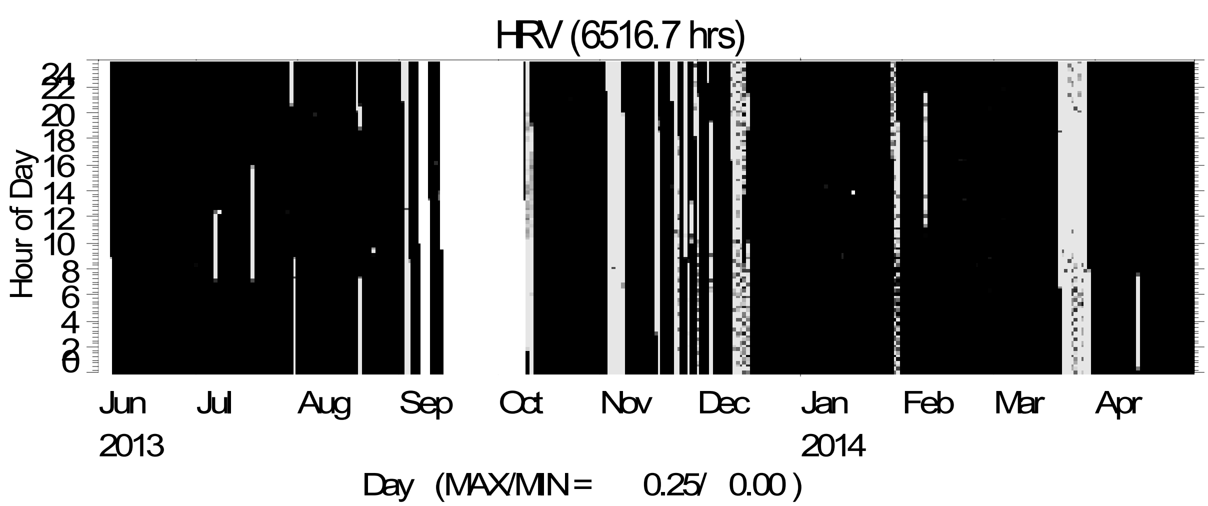


Figure 24 shows the temperature difference between the return air to the HRV (TAB) and the supply air from the HRV (THRV) unit. In practice the TAB should be greater or equal to the THRV in winter and while the opposite is true during summer. But what is observed in Figure 24 is not consistent with the expected trend. The resistance element in the HRV might contribute for the observed higher THRV during winter. Figure 24 also shows that the resistance element was running randomly almost the whole year but it is not expected to work during summer. Thus the accuracy of the measured data for the HRV is suspicious and further investigations are needed.

Figure 24. HRV Temperature Trends at Stuyvesant House

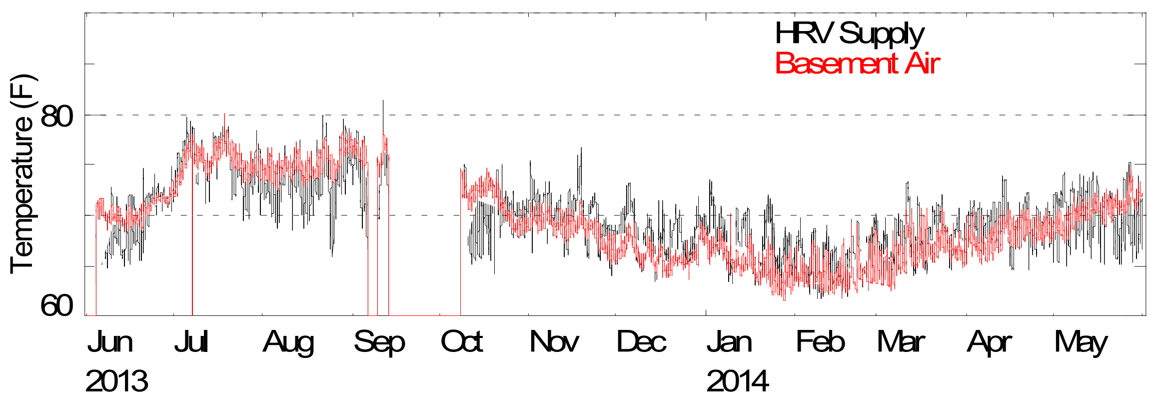


Figure 25 reveals that the HRV supply temperature was independent of the HRV runtime. A linear relationship was observed between HRV supply temperature and HRV return air inlet temperature (Figure 26).

Figure 25. HRV Supply Temperature vs. HRV Runtime at Stuyvesant House

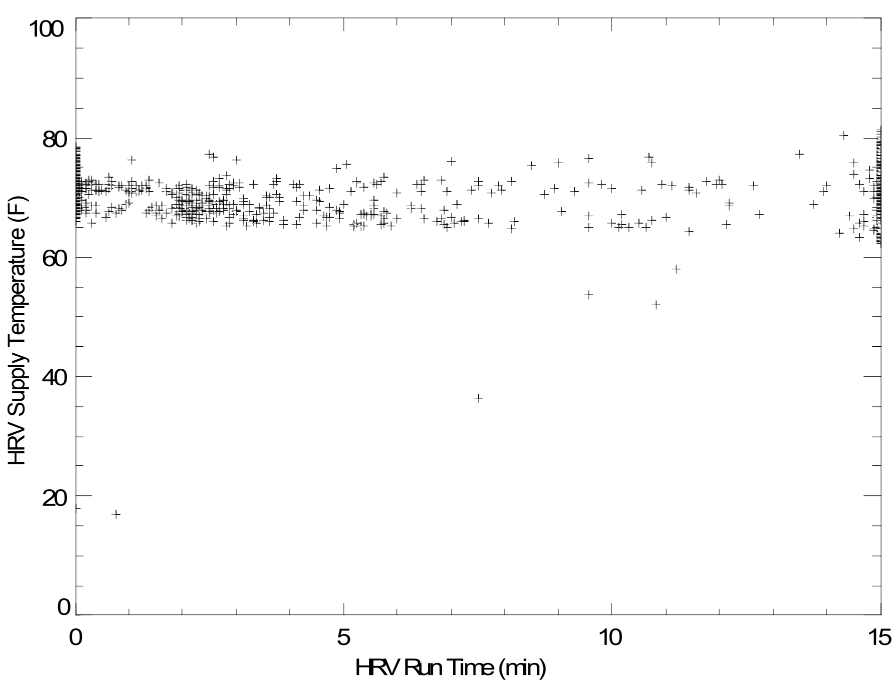
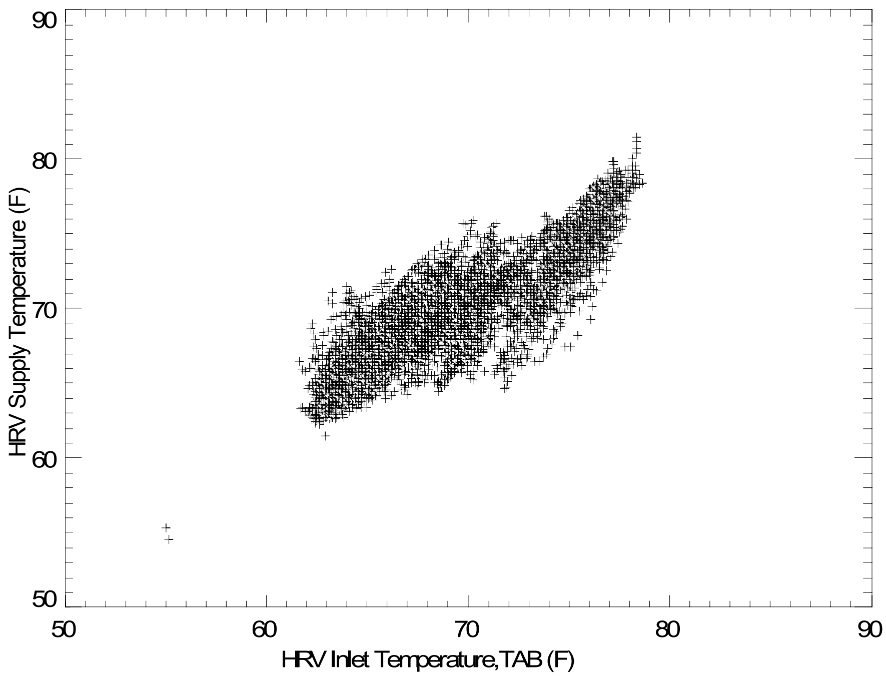


Figure 26. HRV Supply Temperature vs. HRV Inlet Temperature at Stuyvesant House



3.5 Energy Use Compared to PHPP Spreadsheet Model

Monitored energy consumption compared to that predicted (and assumed) by PHPP is shown in Table 15. The monitored data is shown as weather normalized to the 30-year average heating and cooling degree days for comparison to the model and as actual energy used. Data for the missing periods of September and October 2013 were filled in by extrapolating from existing data: DHW and "other" energy were extrapolated linearly for each month from the data collected for each respective month; heat pump heating and cooling energy was extrapolated based on the best fit equations from the collected data and average daily temperature data from the nearby weather station (Albany).

Table 15. Comparison of Energy Use to Model for Stuyvesant House

	Monitored (kWh)	Monitored & Weather Normalized (kWh)	PHPP (kWh)	Variance from model
Total energy	17,030	16,518	10,512	157%
HP energy	3,205	2,709	1,200	226%
Heating	1,908	1,740	936	186%
Cooling	1,297	969	264	367%
DHW energy	2,785	2,785	4,704	59%
Other energy	11,040	11,024	4,608	239%

Compared to PHPP, total weather normalized energy is 57% higher. About 25% of the excess is heat pump energy split roughly equal between heating and cooling. DHW was significantly less than predicted, while "other" energy (lights, appliances, entertainment, etc.) exceeded the model by nearly 2.4 times.

The high miscellaneous energy consumption was not unexpected: both adults work from home-based businesses; one from a workshop where power tools are used and high intensity incandescent lighting is used; and the other from a home office on the loft. Some portion of the miscellaneous energy is also due to the occasional use of resistance heat in the basement studio. These loads were not factored into the PHPP model.

Cooling energy was substantially underestimated. Because of allergies, windows were typically closed with the heat pump running even during relatively cool weather; periods were observed where cooling was operating at high power even with outdoor temperatures below 70°F. For example, there were 190 hours where the heat pump was drawing an average of 400 watts or more with outdoor temperatures between 60 °F and 70°F. The HRV does have a bypass mode, but it was insufficient to fulfill the cooling load without assistance from the heat pump during these periods.

3.6 Homeowner Interview

The homeowners were generally pleased with most systems in the house. The heating system was very comfortable, although they did use some resistance heat in the basement studio. Cooling was rated acceptable, even though only one ¾-ton heat pump was installed for all three levels of the house. Additional cooling capacity was planned, but not installed. The homeowners recognize that their energy bills are somewhat higher than they initially expected due to the nature of their home businesses. The indoor environment was deemed to be excellent with very even heating and cooling, and a lack of hot or cold spots in the living area. While the ventilation performance was generally successful (they rated it as their favorite feature of the home), operating the HRV did involve a learning curve. One exception was reported "stuffiness" in the bedrooms when the doors are closed. Higher airflow into these rooms would be desirable.

3.7 Conclusions for Stuyvesant House

Comfort was generally good, with the exception of some stuffiness reported in the second-floor bedrooms. A single heat pump located high on the second floor of the open space was able to heat and cool the first and second floors adequately, and temper the basement level in winter. A small amount of resistance heat was needed in the basement workshop to maintain wintertime comfort during very cold periods. Overheating due to solar gain in the main living space was not reported to be a problem or observed in the data despite the large high-solar gain windows on the south façade. Some shading from trees and an overhang likely contributed to this overheating.

These homeowners operated their heat pump in a "set-it-and-leave-it" mode, rarely turning it off over the course of the year (it was off for less than 10% of the year). In part, this practice occurred because windows were kept closed to prevent allergens from entering the home. The continuous operation enabled a single ductless heat pump to successfully maintain comfort throughout the living areas of the home over the year.

Total house energy was approximately 50% higher than predicted by PHPP largely due to the more intensive occupant activities (home businesses) and occupant desire to keep windows closed even during periods when free cooling was available. DHW energy was about 40% less than predicted; and heat pump energy was a bit more than double the prediction.

4 Hudson Passive Townhomes

Figure 27. Hudson Passive Townhomes

4.1 Introduction

The Hudson Passive Townhomes consists of two mirror-image, three-bedroom townhomes of 1,614 square feet each. The lower floor contains a living/dining room, kitchen, bathroom, and flex-room. The second floor contains three bedrooms and a bathroom. Each home also has a full, unfinished basement. The street façade is oriented southwest with good solar exposure (Figure 28, Figure 29, and Figure 30).

Figure 28. Hudson Passive Townhomes Street Elevation

Source: BarlisWedlick Architects

Figure 29. Hudson Passive Townhomes First Floor Plan

Source: BarlisWedlick Architects

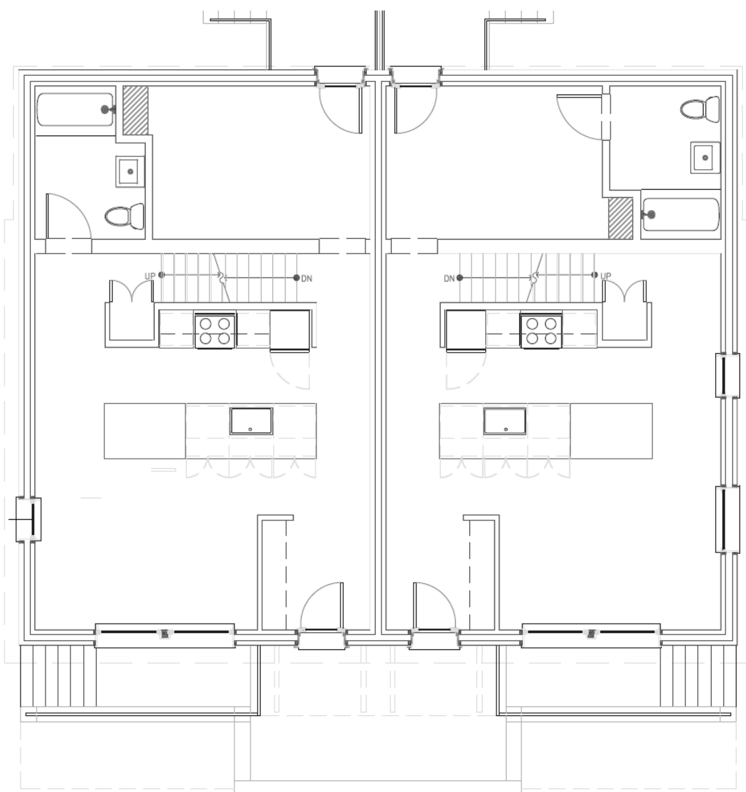
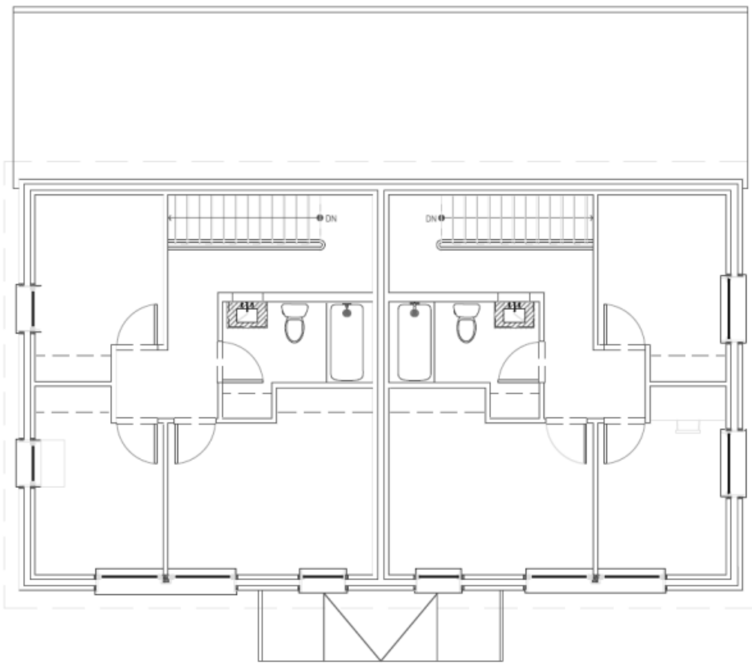


Figure 30. Hudson Passive Townhomes Second Floor Plan

Source: BarlisWedlick Architects



The Hudson Passive Townhomes were built with Passive House features as described in Table 16.

Table 16. Hudson Passive Townhome Specifications

Item	Specification
Slab	R-55 under slab insulation
Foundation wall	R-52 XPS insulation
Exterior walls	Double stud wall with R-43 cellulose insulation
Roof	Main roof R-89 cellulose; rear shed roof R-46 Neopor EPS SIPs
Windows and doors	Intus triple pane overall U-factor 0.15; SHGC 0.62
Infiltration	0.58 ACH50
Heating/cooling system	Mitsubishi ductless heat pump 12 kBtu/hr; SEER 23, HSPF 10.5
Ventilation system	UltimateAir Recouperator ERV
Water heating	Electric storage tank EF 0.93

4.2 Monitoring Approach

This site is divided into two adjacent townhouses. In each house, dataloggers recorded heat pump, DHW, ERV and total house power. A detailed list of the measurement points for each townhome is given in Table 17. Figure 31 depicts the monitoring equipment installed at the Hudson Passive Townhomes.

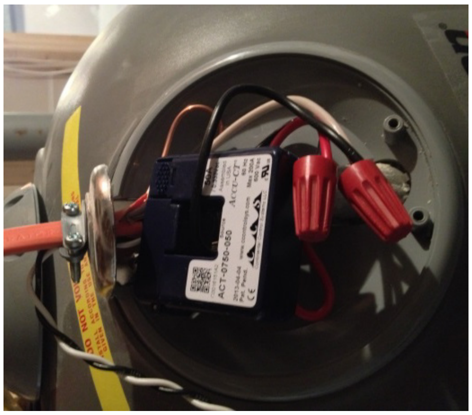
Table 17. Hudson Passive Townhomes Monitoring Points

Data Point	Description	Instrument
T/RHAI1	Room air temperature and RH – first floor (left unit)	Hobo UX100-011
T/RHAI2	Room air temperature and RH – first floor (right unit)	Hobo UX100-011
TAI3	Room air temperature – bedroom second room (left unit)	Hobo U12-001
TAI4	Room air temperature – bedroom second room (left unit)	Hobo U12-001
TAI5	Basement air temperature	Thermistor
WHP	Heat Pump Power	kWh meter
WDHW	DHW Power	kWh meter
WT	Total House Power	kWh meter
SHRV	HRV Fan Runtime	minutes
SRHT	HRV Resistance Element Status	minutes

Figure 31. Monitoring Equipment at Hudson Passive Townhomes

(a) CTs to monitor DHW power; (b) CTs to monitor total house power; (c) Current status for HRV; (d) Hobos to measure indoor temperature on the second floor, and temperature and RH on the first floor; (e) Dataloggers

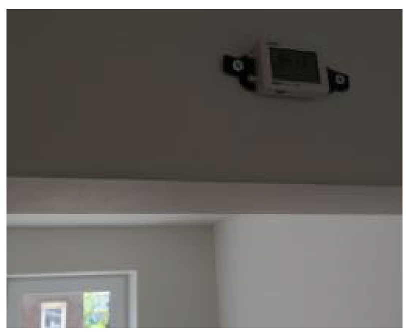
(a)



(b)

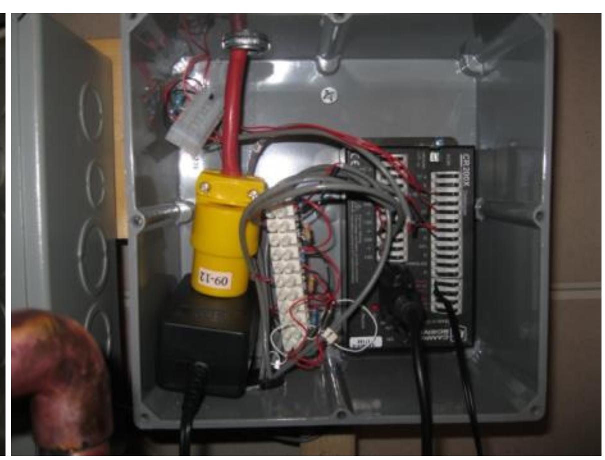
(c)

(d)



(e)

(e)



4.2.1 Space Conditioning Equipment Operation

Both homes use a single-head, ductless mini-split heat pump (Mitsubishi MSZ-FE12NA) located high on the wall on the first floor at the base of the stair to the second floor (Figure 32). The cooling capacity range is 2,800-12,000 Btu/hr and in heating 3,000 to 21,000 Btu/hr.

Figure 32. Heat Pump Indoor Unit in Hudson Passive Townhomes

As expected, daily heat pump energy consumption increased with decreasing daily average temperature below 50 °F and increased with increasing daily average temperature above 60 °F (Figure 33 through Figure 36). The wide scatter of points reflects the occupant’s intermittent use of the heat pump (they only turned it on when home). The plot for Townhome B shows somewhat less scatter than Townhome A; the residents in Townhome B used the heat pump more consistently.

Figure 33. Heating Load Line at Townhome A

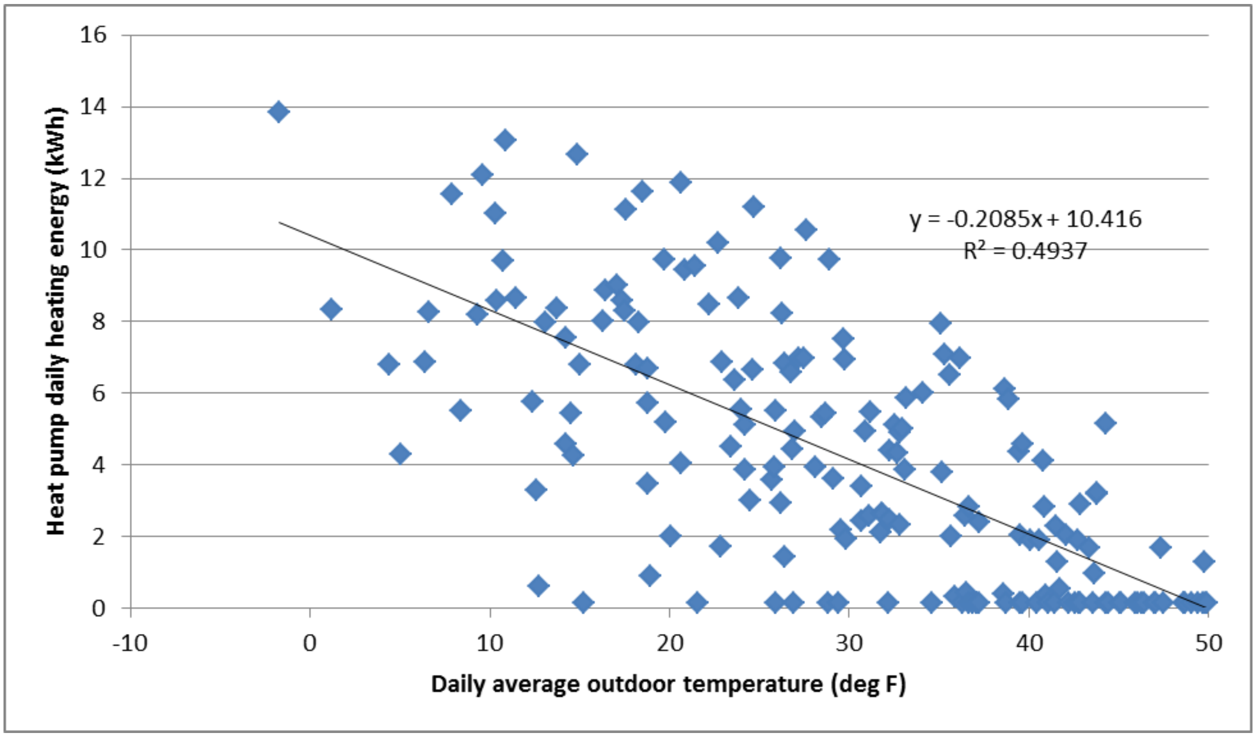


Figure 34. Cooling Load Line at Townhome A

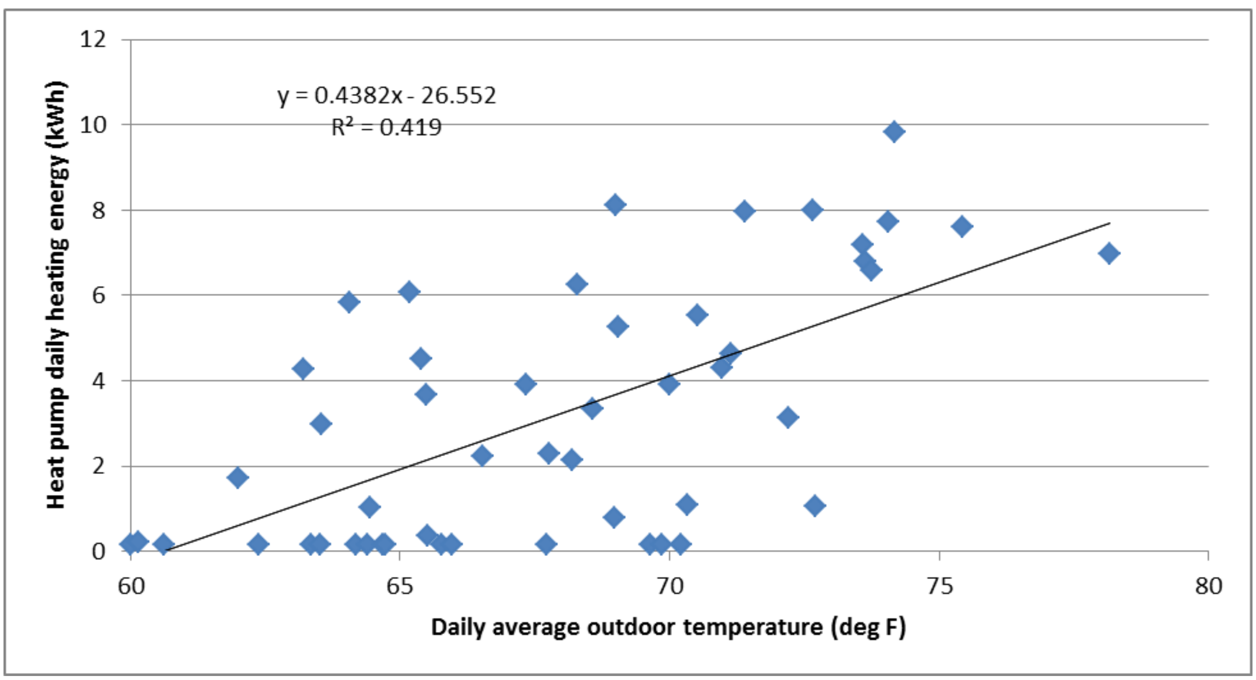


Figure 35. Heating Load Line at Townhome B

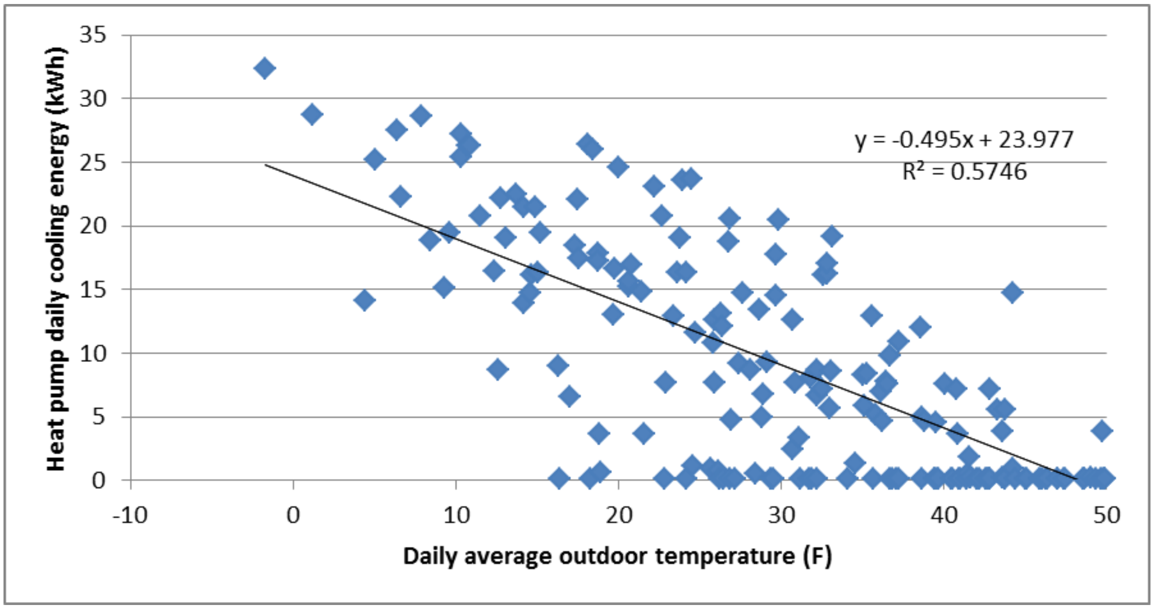
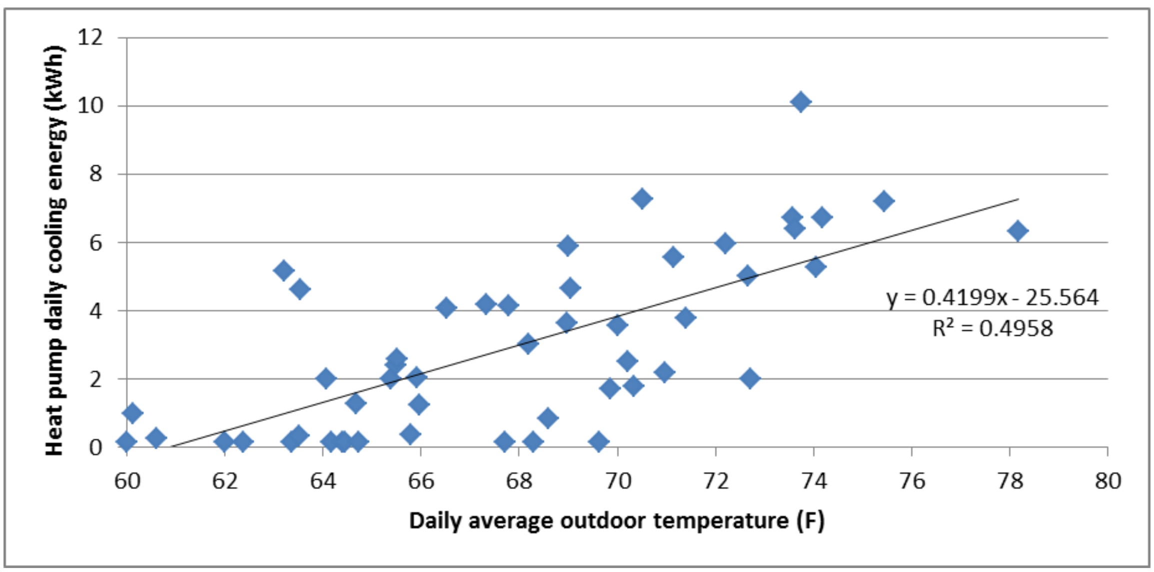


Figure 36. Cooling Load Line at Townhome B



The maximum power draw of these units is approximately 2 kW. Because of the on-off nature of the heat pump operation, the heat pump was often operating at its maximum output, despite the fact that the unit was oversized relative to the home's calculated load at design temperature.

In Townhome A, more so than in Townhome B, the heat pump was operating at maximum heating power for many hours with outdoor temperatures as high as the 40s. In cooling mode, the unit operated a lower power levels, even though the second floor often did not reach setpoint, because the first floor air temperature satisfied the thermostat. The minimum power draw (standby power when the unit was turned off) was 6-8 watts.

Figure 37. Heat Pump Power as a Function of Outdoor Temperature for Townhome A

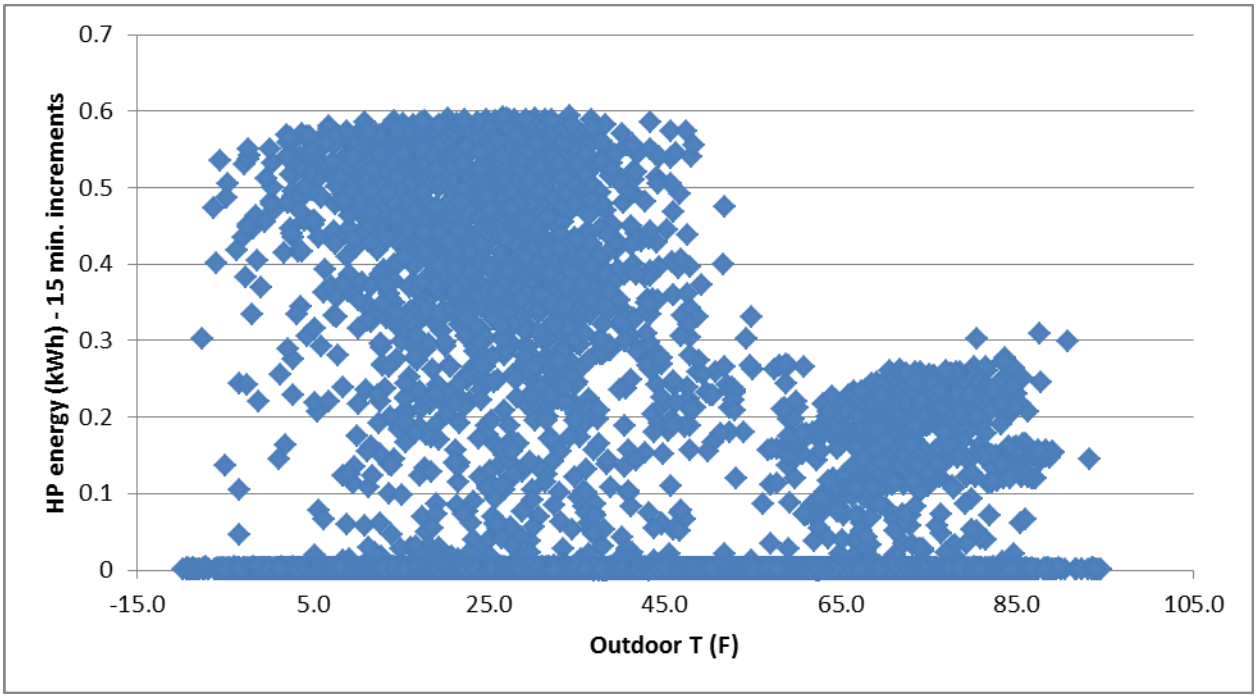
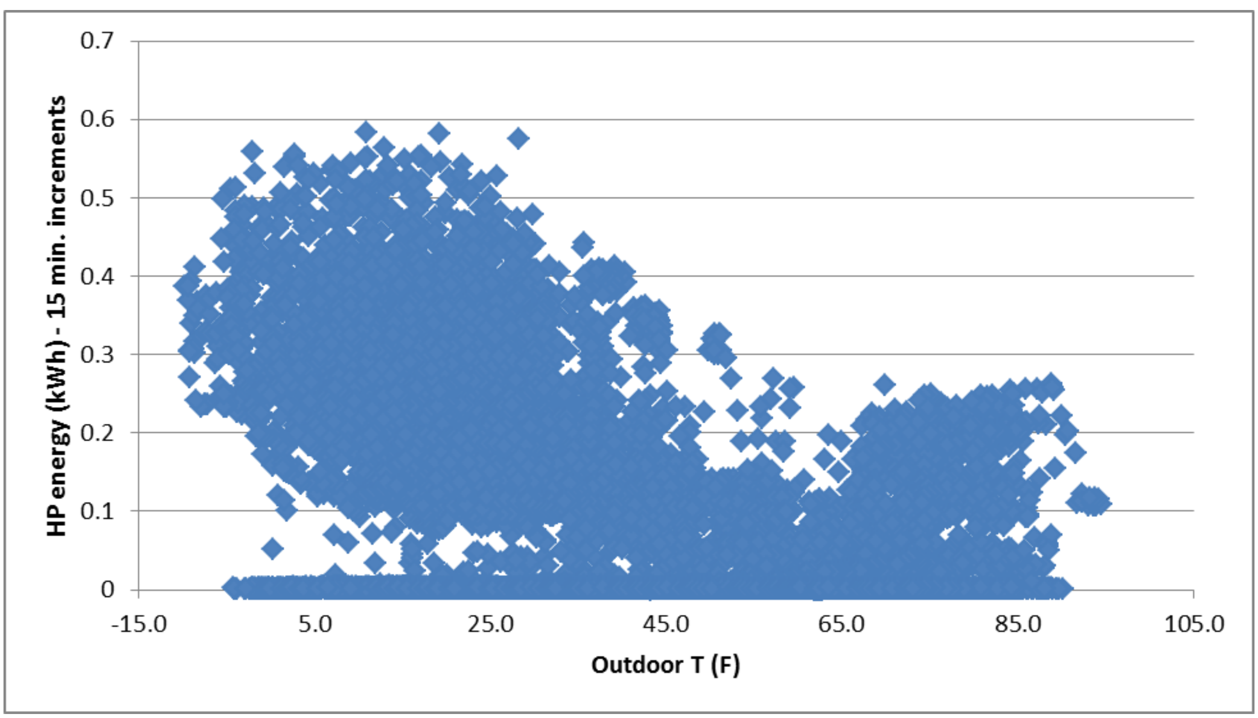


Figure 38. Heat Pump Power as a Function of Outdoor Temperature for Townhome B



4.2.2 Daily Energy Use Over the Year

Figure 39 and Figure 40 show energy use by major segment over the course of the year. Total house power (green) increased in winter due to heat pump use and more DHW energy use. Non-heat pump/DHW energy (purple) was fairly constant throughout the year. In Townhome A, DHW energy increased slightly starting in late 2013: occupancy started at three and grew to six people over the course of the monitoring period. Daily energy use was typically between 25 and 50 kWh throughout the year for 244 and between 30 and 60 kWh for 246 (four occupants).

Figure 39. Daily Energy Use Compared to Outdoor Temperature for Townhome A

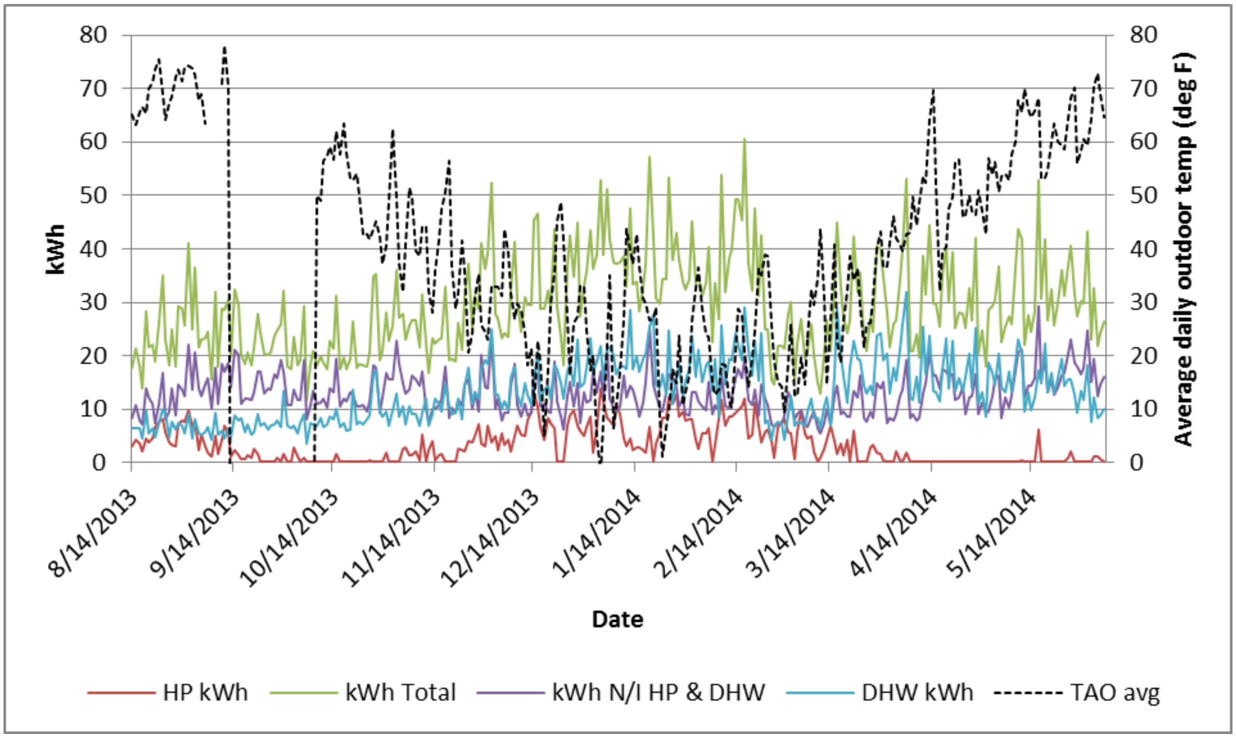
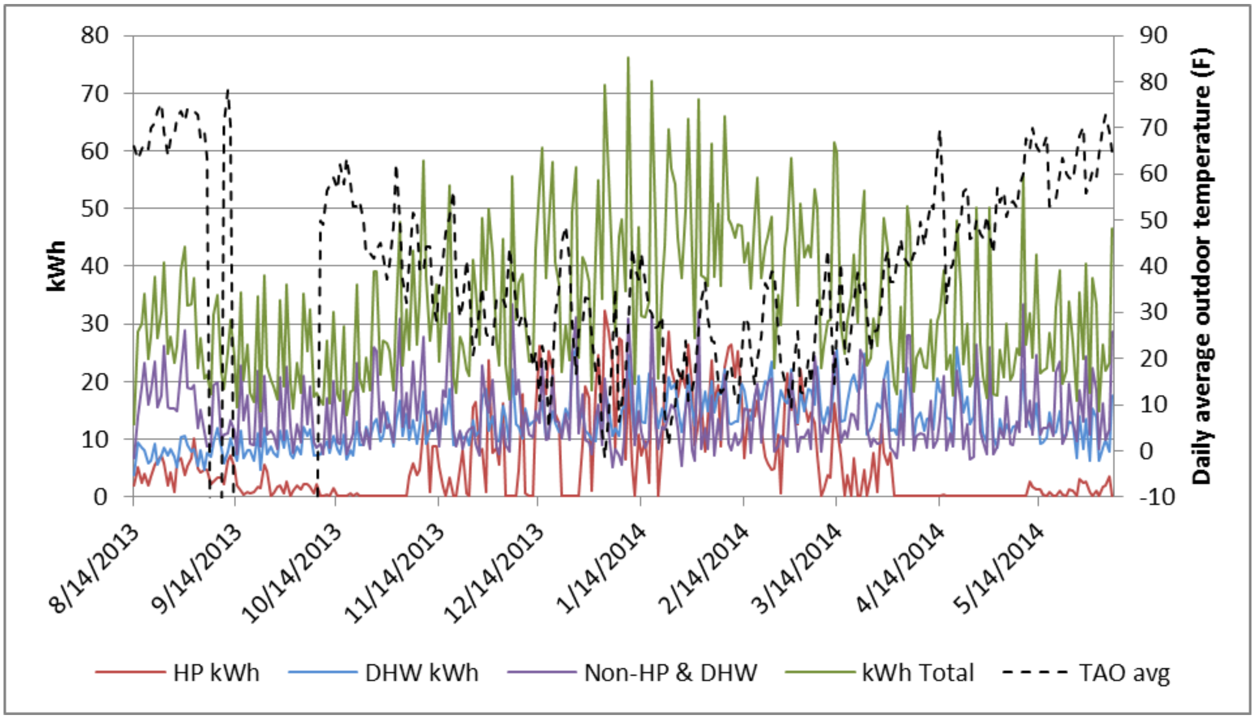


Figure 40. Daily Energy Use Compared to Outdoor Temperature for Townhome B



To look for evidence of supplemental electric space heating the following plots of non-heat pump/DHW daily energy vs. outdoor temperature were generated (Figure 41 and Figure 42). Total daily energy use not including heat pump and DHW showed no correlation with outdoor temperature during heating season. Supplemental resistance heating use is not obvious in these data for either home. If the residents operated their resistance heaters similarly to the way they operated their heat pumps, it is likely that use was intermittent and for short periods, minimizing impact on energy usage.

Figure 41. Plug and Appliance Energy During the Heating Season for Townhome A

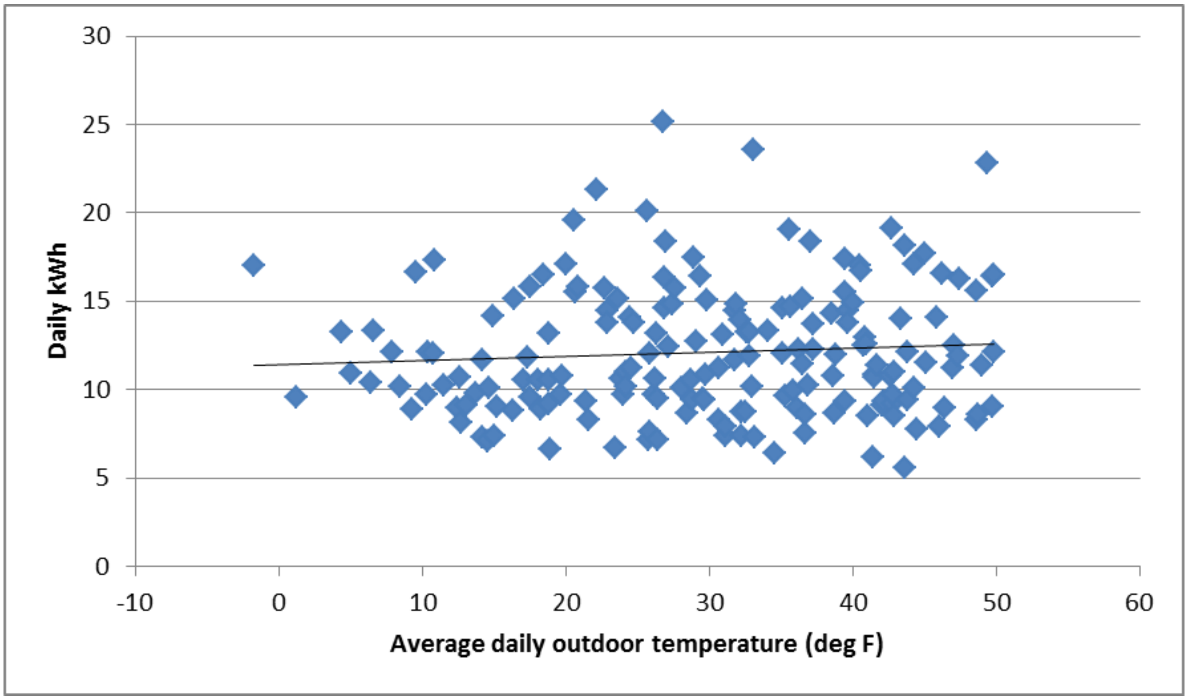
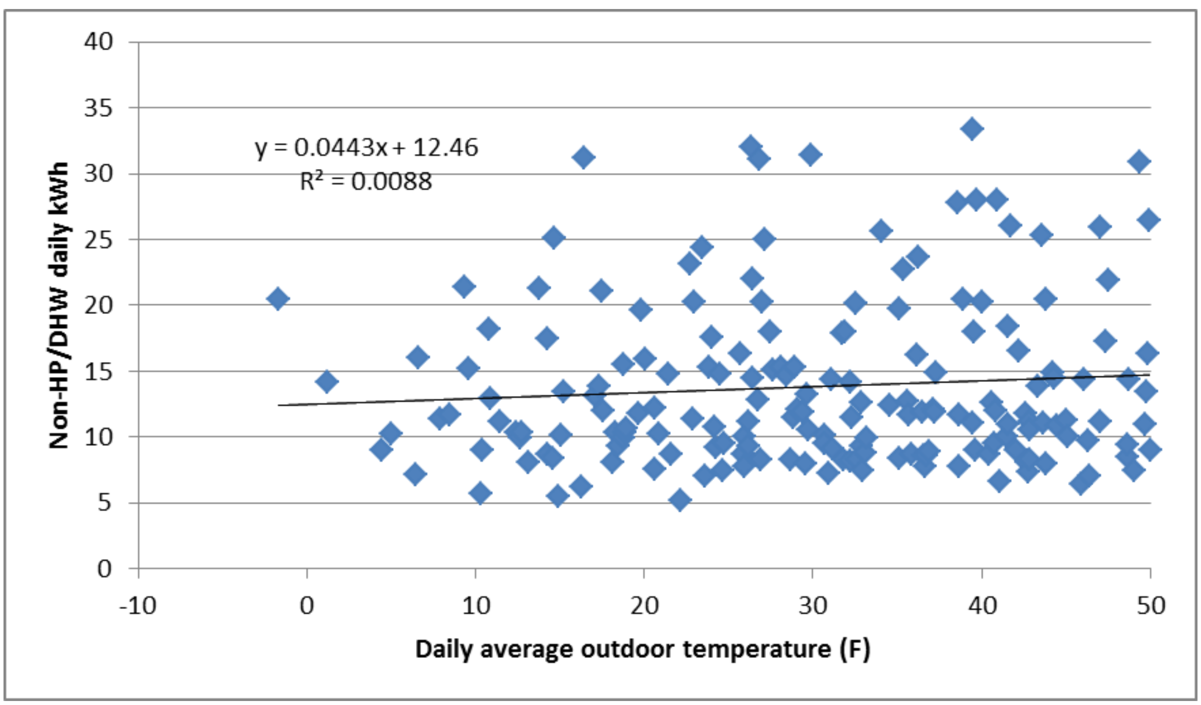


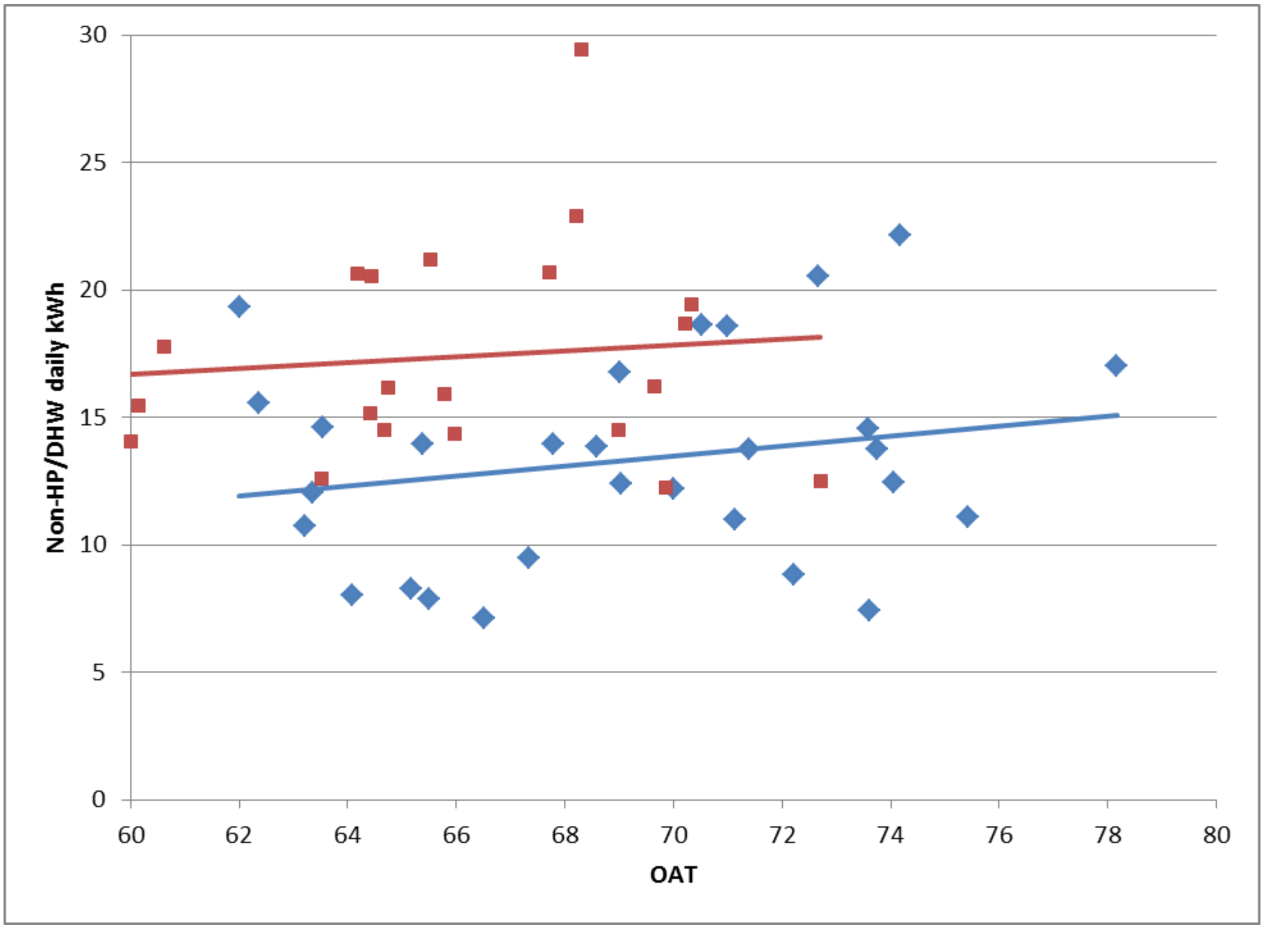
Figure 42. Plug and Appliance Energy During the Heating Season for Townhome B



Comparison of non-HP/DHW energy for Townhome A during the 2013 and 2014 cooling seasons shows an increase from about 14 kWh per day to 17 kWh per day (Figure 43). Part of this increase could be due to the addition of the three floor transfer fans at 25 watts each and the reported increase in occupancy of the home.

Figure 43. Plug and Appliance Energy during the 2013 and 2014 Cooling Seasons for Townhome A

Occupied air temperature (OAT) before (blue) and after (red) installation of transfer fans.



4.3 HRV Operation

In Townhome A, HRV operation was nearly continuous except for a few weeks in August 2013 and four brief periods in October and November 2013 (Figure 44). In Townhome B, HRV operation was nearly continuous except for five brief periods in 2013 (Figure 45).

Figure 44. ERV Operation for Townhome A

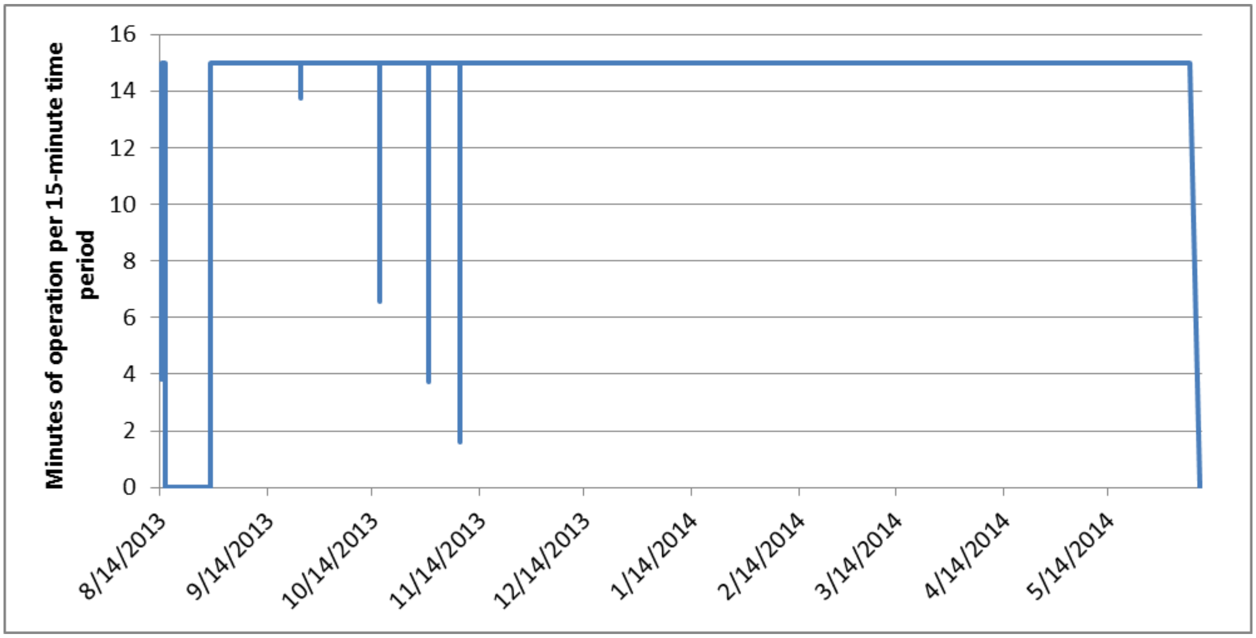
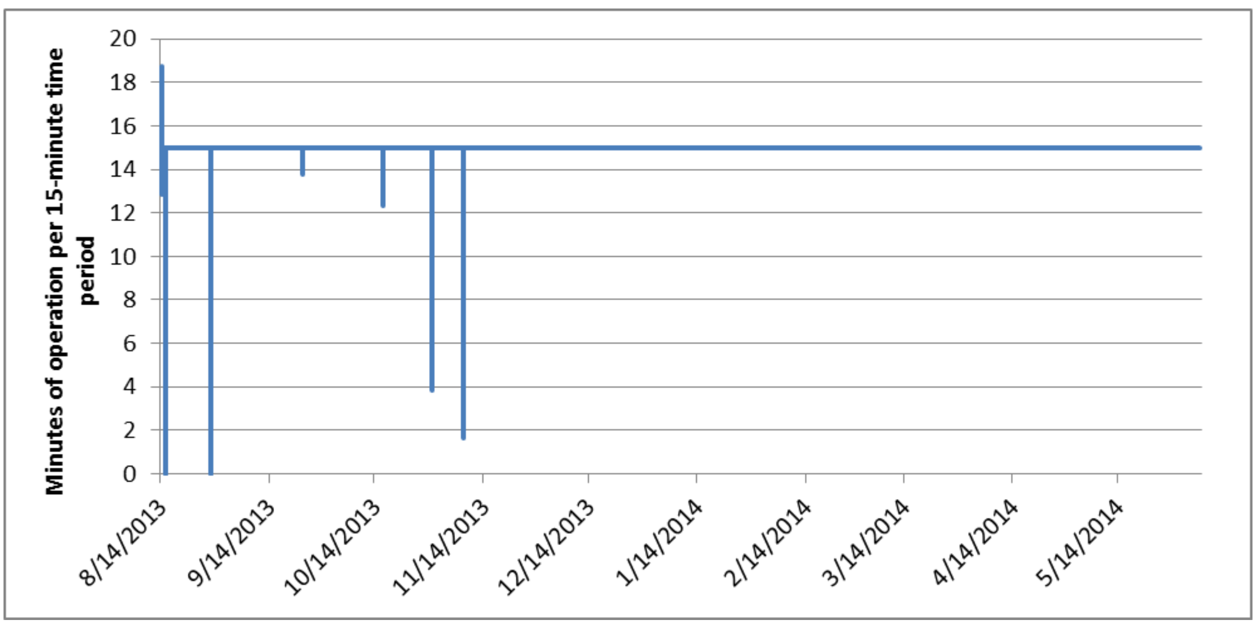


Figure 45. ERV Operation for Townhome B



4.4 Total Energy Use Comparison

Monitored energy consumption compared to that predicted by REM/Rate and PHPP is shown in Table 18 and Table 19. The models have been adjusted to reflect the approximate average number of occupants that lived in the homes during the monitoring period (Townhome A= 6, Townhome B = 4). The monitored data is shown weather normalized to the 30-year average for comparison to the models and as actual energy used.

Compared to REM/Rate, total weather normalized monitored energy for Townhome A is within 11%; DHW is within 9% and other energy is within 12%. Heat pump energy was predicted by REM/Rate to be about double the weather normalized monitored energy. The Passive House Planning Package (PHPP) predicted less total energy than used; specifically, PHPP predicted less DHW energy and far less "other" energy. Both of these components are highly depending on occupant behavior.

Also shown in Table 18 is the projected energy consumption for the same house designed to code minimum specifications (2010 Energy Conservation Code of New York, approximately equivalent to the 2009 International Energy Conservation Code (IECC). Predicted total energy for the code minimum design is about 2.7 times the monitored use, weather normalized.

Table 18. Comparison of Total Energy Use for Townhome A

Units are kilowatt-hours.

	Monitored	Monitored & Weather Normalized	PHPP	REM/Rate Passive Design	REM/Rate code minimum
Total energy	10,821	10,628	8,583	11,840	28,566
HP energy	1,269	1,077	3,012	2,139	17,128
Heating	747	678	2,605	1,114	15,750
Cooling	522	399	407	1,026	1,378
DHW energy	4,810	4,810	3,923	4,396	5,074
Other energy	4,741	4,741	1,648	5,305	6,364

Compared to REM/Rate, total weather normalized monitored energy for Townhome B is within 4%; DHW is within 13% and other energy is within 1% (Table 19). Heat pump energy is within 6% of the weather normalized monitored energy. The Passive House Planning Package (PHPP) predicted less total energy than used; specifically, PHPP predicted less DHW energy and far less "other" energy. Again, both of these components are highly depending on occupant behavior.

Table 19. Comparison of Total Energy Use for Townhome B

kWh	Monitored	Monitored & Weather Normalized	PHPP	REM/Rate Passive Design
Total energy	12,031	11,396	6,573	10,932
HP energy	2,123	1,844	2,815	1,964
Heating	1,598	1,451	2,408	1,231
Cooling	516	394	407	733
DHW energy	4,750	4,750	2,857	4,162
Other energy	5,158	5,158	900	4,806

4.5 Comfort

A site visit was made to both homes in December 2013. The following observations were made about Townhome A (Figure 46 and Figure 47):

- Consistent daily on/off pattern to the heat pump: it is on for a few hours each evening.
- Heat pump operational pattern is consistent with a high heating set point (at least 75 °F) and the user turning it on (6:30 p.m.) and off (9:30 p.m.) rather than leaving it at a comfortable set point.
- During this heating season period, the 1st and 2nd floor temperatures were similar (2nd floor slightly warmer); however when the heat pump turns on the 1st floor temperature spikes and the 2nd floor temperature begins to rise very gradually (see Fig. 46) .
- No evidence of resistance space heater use was observed in the data or during the site visit.

Figure 46. Sample Heating Season Temperatures – Fall 2013 for Townhome A

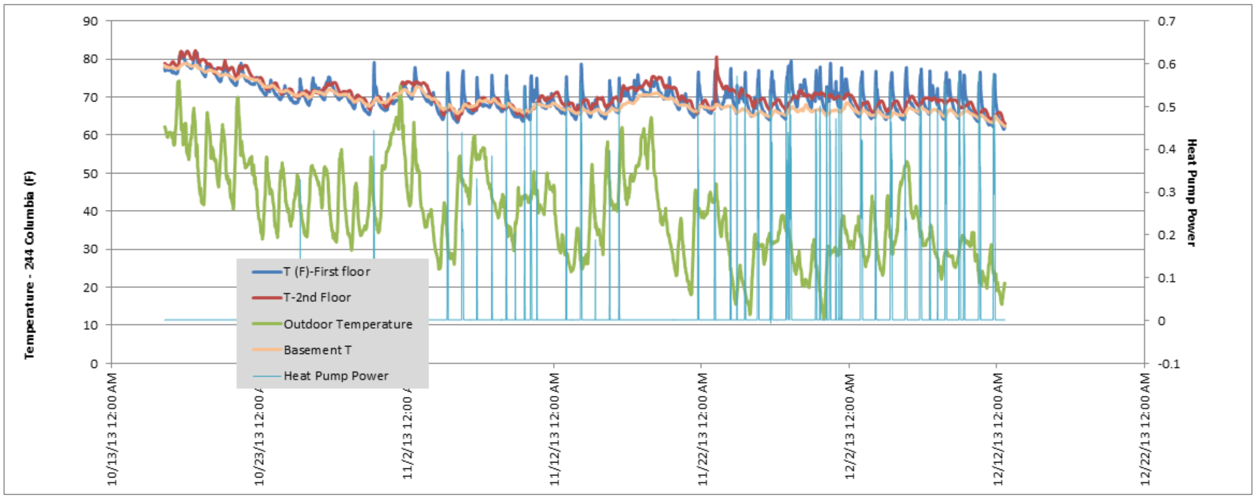
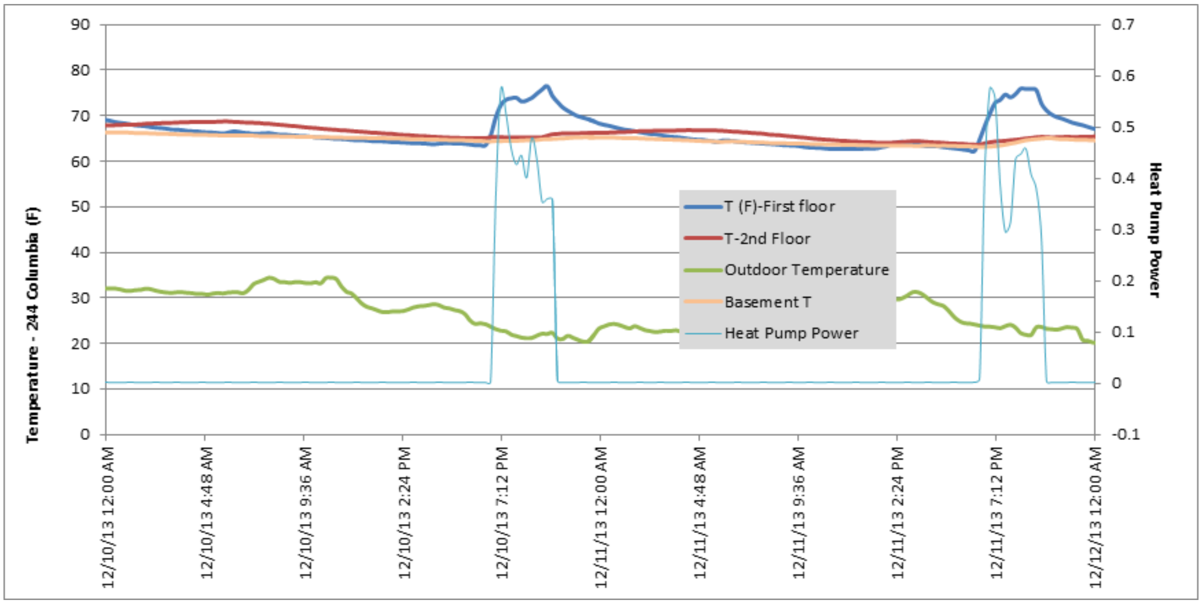


Figure 47. Detail Heating Season Temperatures – December 2013 for Townhome A



The following observations were made about Townhome B (see also Figure 48):

- Resident complained that the home is too cool and the heat pump is not providing enough heat.
- The second floor is slightly warmer than the first floor.
- The data indicate that the resident is turning the heat pump on and off and possibly adjusting set point temperature frequently rather than leaving it at a comfortable set point (Figure 48).
- The heat pump is on for a day or two at a time, then off for a similar length period. Indoor temperature increases to over 70 °F on the first floor when the heat pump is on. Note that from Dec. 4-8 there was no heat pump activity. Although outdoor temp did spike to 50 °F over this period, there was significant time below 40 °F outside with no drop in indoor temperature.
- No evidence of resistance space heater use was observed in the data or during the site visit.

Figure 48. November-December 2013 Operation for Townhome B

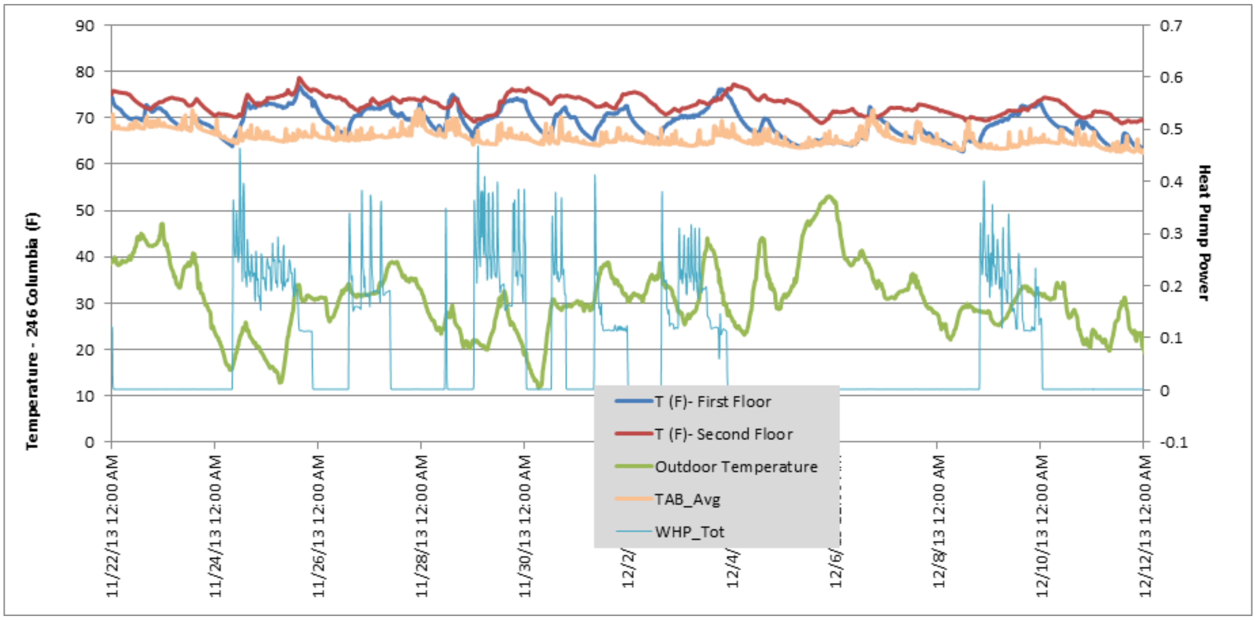


Figure 49 and Figure 50 show other typical winter periods in early 2014 for Townhomes A and B, respectively.

Figure 49. Sample Heating Season Temperatures and Heat Pump Operation for Townhome A

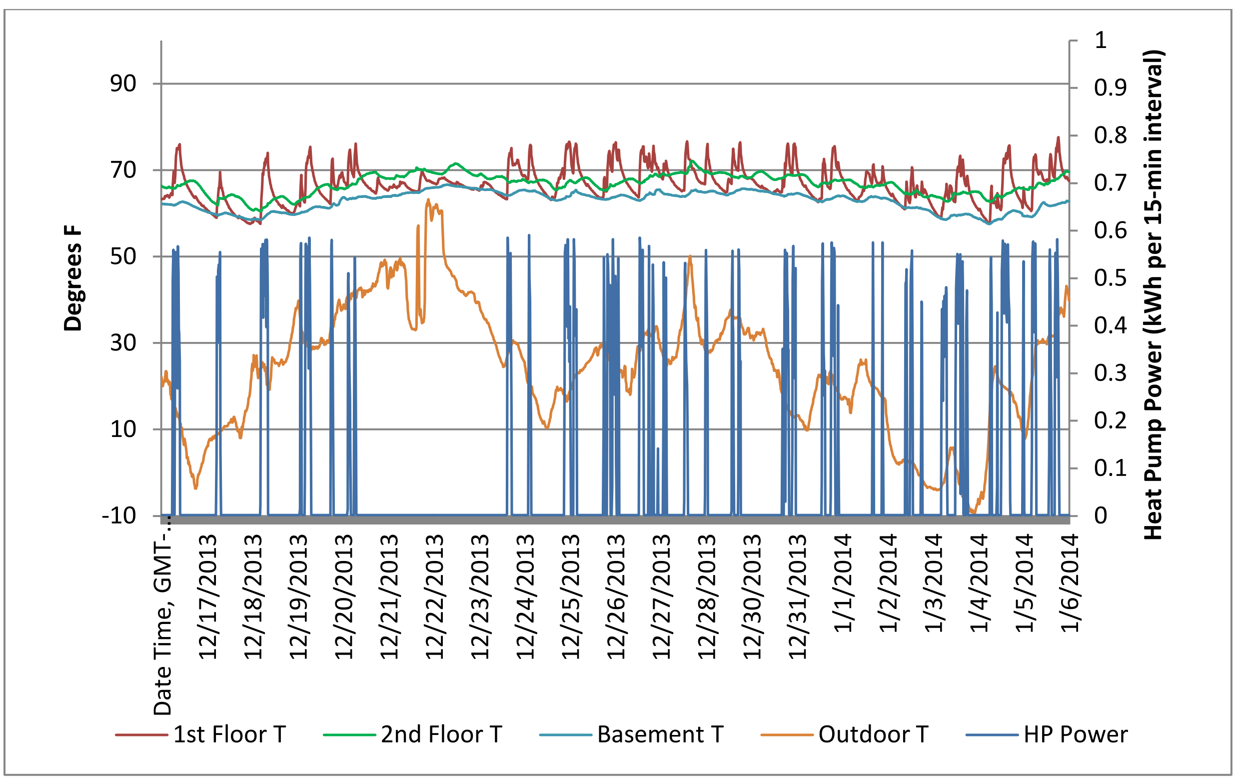
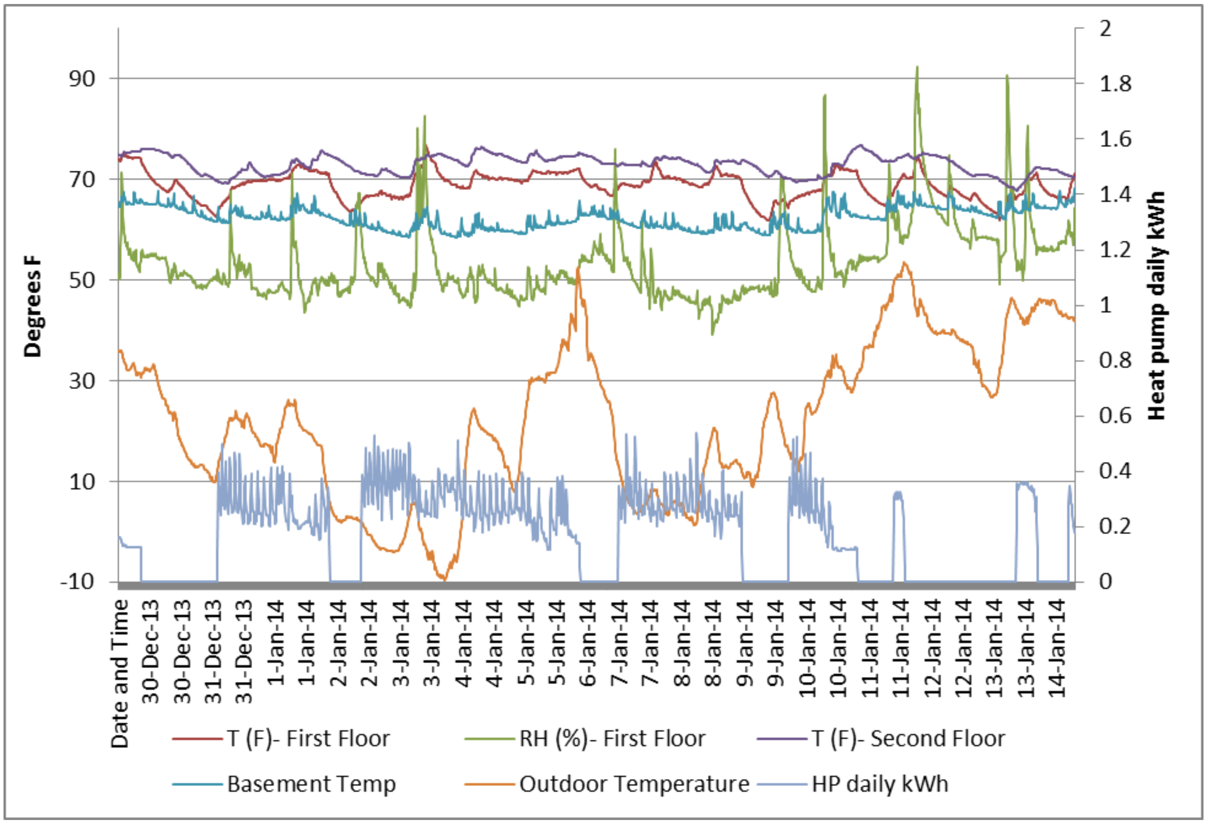


Figure 50. Sample Heating Season Temperatures and Heat Pump Operation for Townhome B



The Townhome A data show that the first floor temperatures were controlled closer to the desired setpoint than the second floor temperatures, which were warmer in summertime and slower to react to the activation of the heat pump in wintertime.

In the heating season (the first floor temperatures (red line) reacted swiftly to the heat pump activation (the homeowners tended to turn off the heat pump when leaving for the day). The heat pump maintained temperatures of nearly 70°F on the first floor even during periods of extremely cold outdoor temperatures – when it was on. Inside temperatures dipped to the high 50s on a few occasions when the heat pump was turned off. Temperatures on the second floor were more stable, showing only slight increases when the heat pump turned on but declining much less significantly when off. Stratification as well as daytime solar gain on the second floor may have contributed to higher daytime temperature upstairs when the heat pump was off. Residents reported use of space heaters as needed on the second floor, although as previously noted, this use was not obvious in the energy data.

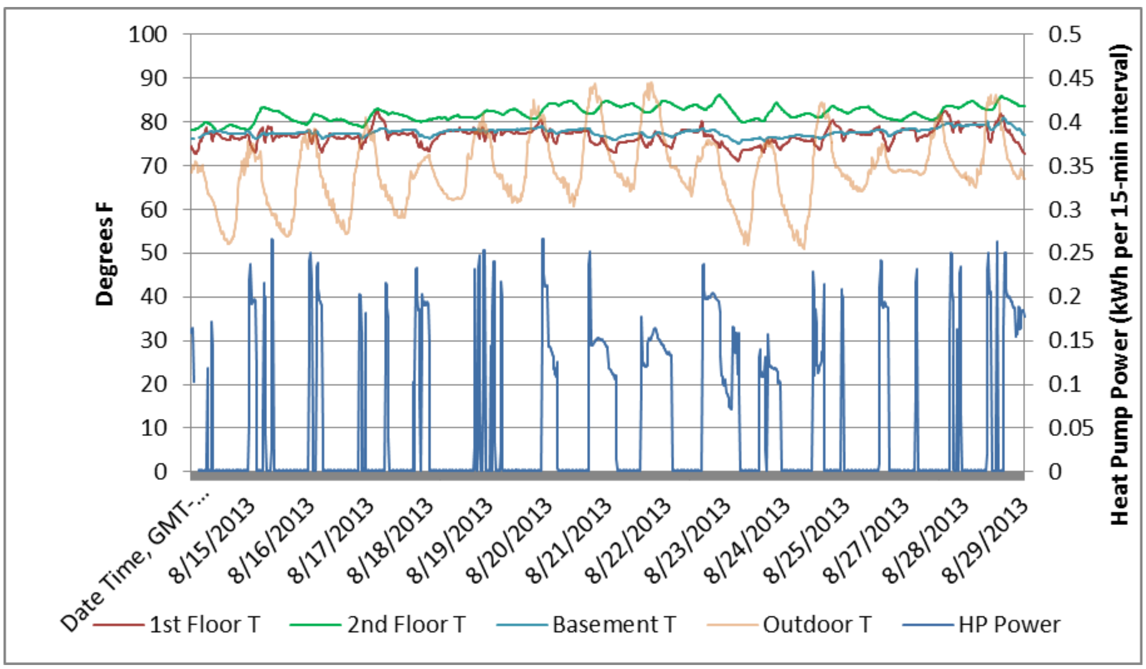
In Townhome B, the second floor was warmer in the heating season, the opposite of conditions found at Townhome A. When the heat pump was on, temperatures were generally between 70 °F and 75 °F on both floors. The homeowners in Townhome B also tended to turn off the heat pump when leaving for the day, however they used it approximately twice as much as the Townhome A owners.

The indoor temperatures in townhome B never dropped below the mid-60s even when the heat pump was off, presumably because of the longer operating times in Townhome B. Dramatic spikes in RH are possibly the result of cooking events.

4.6 Sample Cooling Season Temperatures

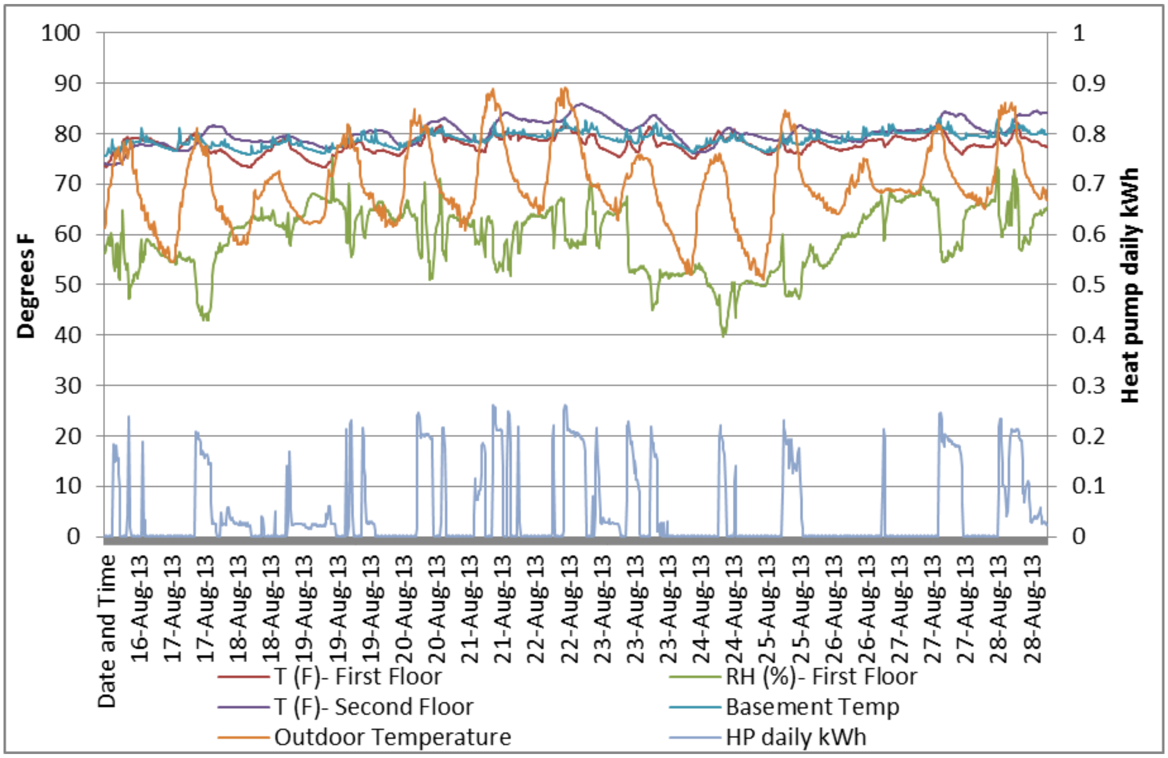
During the summer cooling season, the heat pump in Townhome A typically achieved a first floor temperature in the mid-70s when on, compared to a typical setpoint reported by the residents of 75 °F. The first floor and basement temperatures were very close as seen in the sample cooling season plot (Figure 51). During periods of very high outdoor temperature, the heat pump ran for extended periods at high power. The second floor was consistently 4-8 °F warmer than the first floor, with temperatures often in the low 80s. This difference was the primary complaint of the residents: that the bedrooms were too warm during hot weather. Note that field observations reported that the residents did not often open their windows and this is evident in the figure; there were many periods where the second floor temperature is much warmer than the outdoor temperature.

Figure 51. Sample Cooling Season Temperatures for Townhome A



During the summer cooling season, this sample data showed that the heat pump in Townhome B was operated less frequently. First-floor temperatures were generally in the mid-to-high-70s when the heat pump was on. Second-floor temperatures reached into the low 80s with the heat pump on during the hottest weather. Interestingly, the basement temperature was generally between the first and second floor temperature during this period (Figure 52).

Figure 52. Sample Cooling Season Temperatures and Heat Pump Operation for Townhome B



4.7 Comfort Data Analysis

In Townhome A, the heat pump was operating 11% of the time over the period from August 14, 2013 to June 9, 2014 when heat pump data was logged. This is consistent with the resident reports that they operated the heat pump only as needed and when home. Table 20 and Table 21show the amount of time that indoor temperatures were out of normal comfort range, as a percent of time that the heat pump was on and as a percentage of total monitoring time.

Table 20. Percent of Time Temperatures Were Out of Comfort Range – When Heat Pump Was On in Townhome A

When the heat pump was on…	First floor	Second floor
% cooling season temperature over 78 °F	18%	100%
% heating season temperature below 68 °F	21%	73%

Table 21. Percent of Time Temperatures Were Out of Comfort Range – Total Monitoring Time in Townhome A

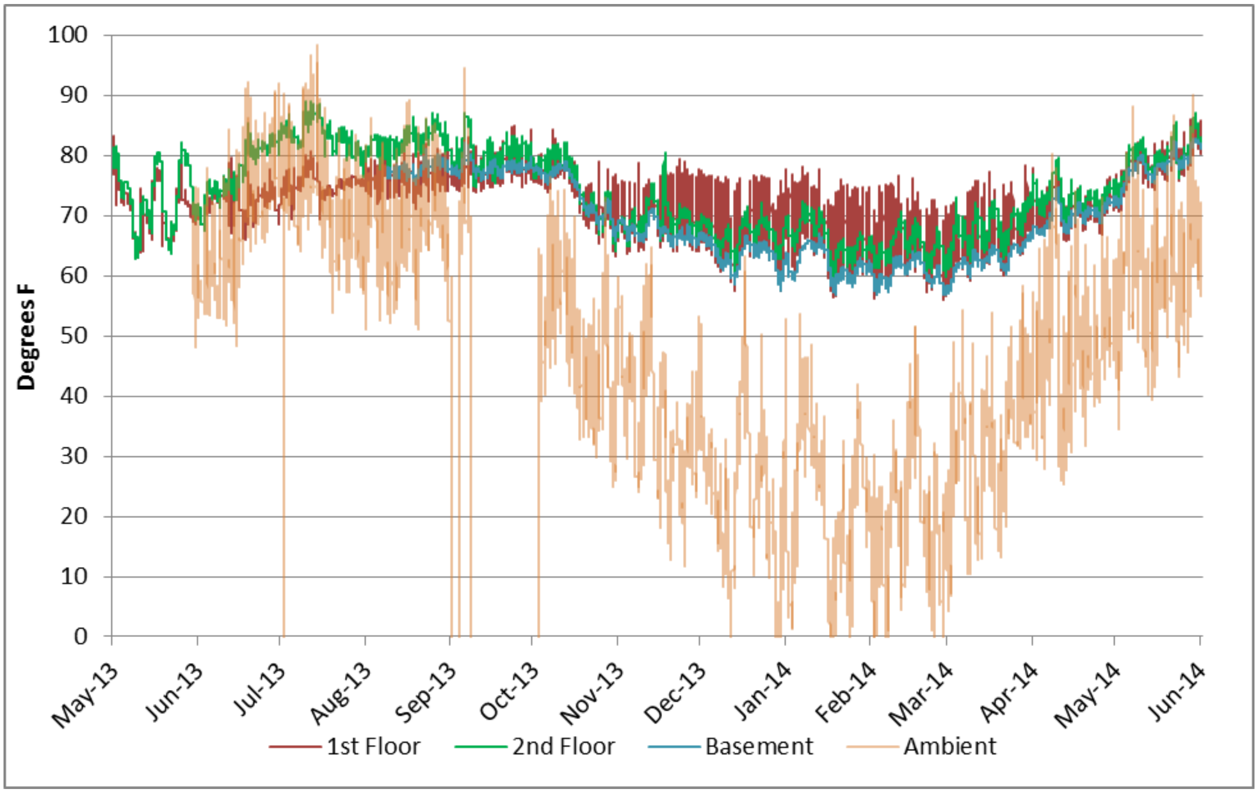
Total monitoring time…	First floor	Second floor
% cooling season temperature over 78 °F	11%	23%
% heating season temperature below 68 °F	31%	26%

The heat pump was on for a small portion of the year as seen in Table 22. Figure 53 shows the temperature data for the full year.

Table 22. Percent of Time Heat Pump Was On in Townhome A

Conditions	% total monitored time	% time heat pump on during heating or cooling conditions outside
Cooling conditions: outdoor daily average temperature above 60 °F	18.6%	16.1%
Heating conditions: Outdoor daily average temperature below 50 °F	70.1%	10.7%
Total period (all outdoor temperatures)		10.7%

Figure 53. Temperatures for Entire Monitoring Period for Townhome A



In Townhome B, the heat pump was operating 36% of the time over the period from Aug 14, 2013 to June 9, 2014 when heat pump data was logged. Tables 23, 24, and 25 show the amount of time that indoor temperatures were out of normal comfort range, as a percent of time that the heat pump was on and as a percentage of total monitoring time.

Table 23. Percent of Time Temperatures Were Out of Comfort Range – When Heat Pump On for Townhome B

When the heat pump was on…	First floor	Second floor
% cooling season temperature over 78 °F	44%	91%
% heating season temperature below 68 °F	11%	2%

Table 24. Percent of Time Temperatures Were Out of Comfort Range – Total Monitoring Time for Townhome B

Total monitoring time…	First floor	Second floor
% cooling season temperature over 78 °F	11%	19%
% heating season temperature below 68 °F	15%	1%

Table 25. Percent of Time Heat Pump Was On in Townhome B

Conditions	% total monitored time	% time heat pump on during heating or cooling conditions outside
Cooling conditions: outdoor daily average temperature above 60 °F	18.6%	30%
Heating conditions: Outdoor daily average temperature below 50 °F	70.1%	40%
Total period (all outdoor temperatures)		36%

4.7.1 Relative Humidity

Another metric of comfort is relative humidity. The humidity control metric used by (Rudd 2013) and others is the number of hours with interior relative humidity levels over 60%.

For the first floor of Townhome A, that number was 37%. For Townhome B (also first floor), that number was 19%. In both houses, much of the time over 60% was during winter (Figure 54 and Figure 55), indicating that high internal moisture loads may have contributed to high relative humidity. This is also consistent with the on-off operation of the heat pumps. Note that the residents did not specifically express any humidity complaints, although they may have been more comfortable at higher summer and lower winter temperatures if the humidity was lower.

Figure 54. Relative Humidity for Entire Monitoring Period in Townhome A

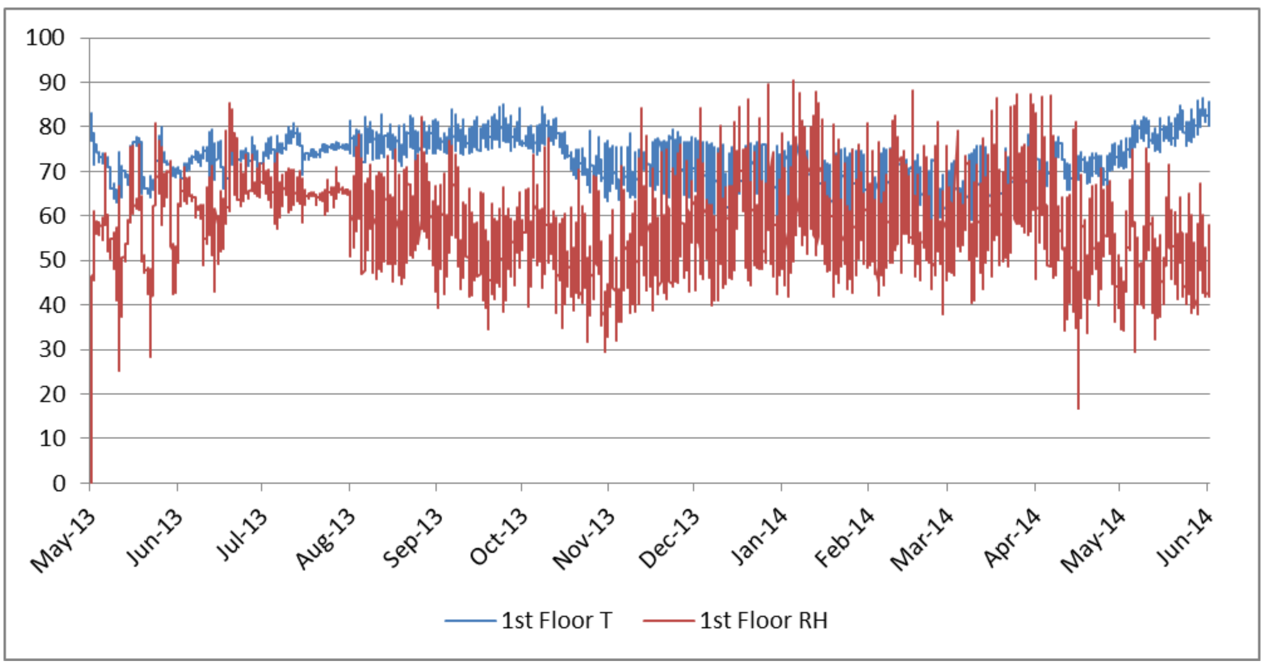
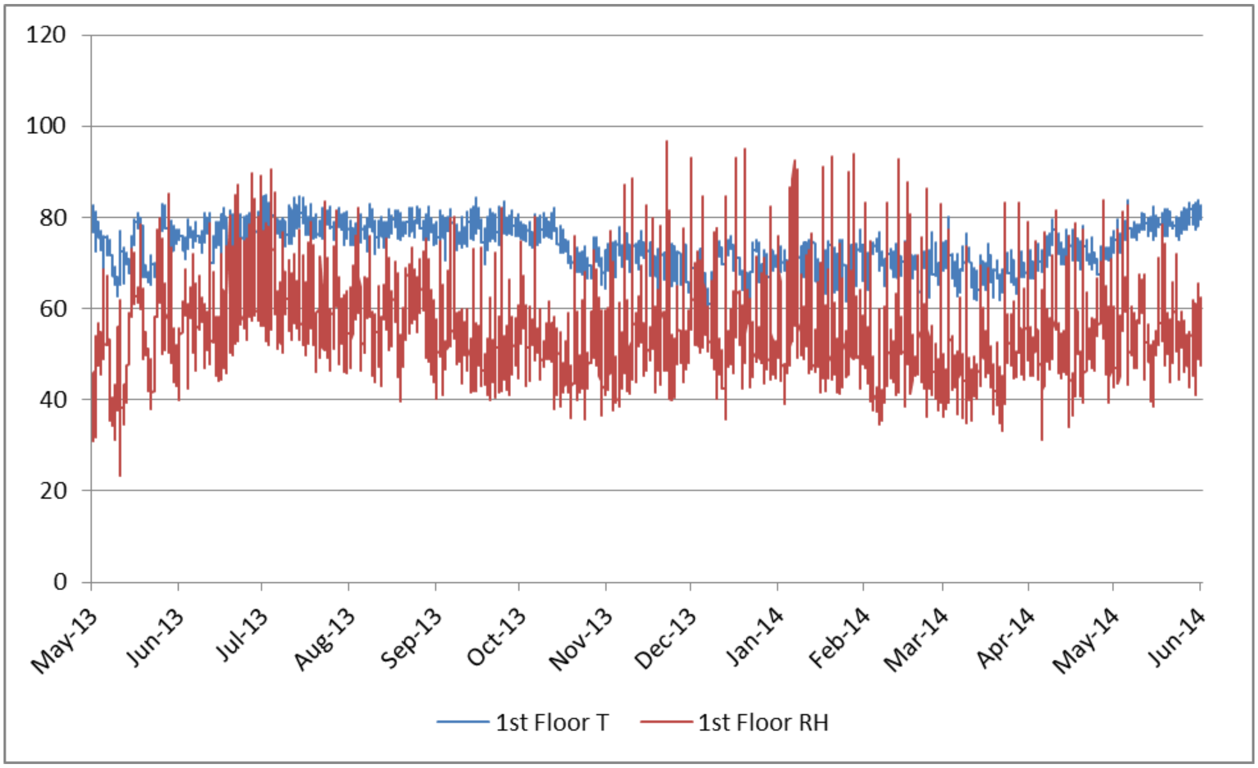


Figure 55. Relative Humidity for Entire Monitoring Period in Townhome B



4.8 Resident Interviews

Townhome A: This resident was generally satisfied with all aspects except for the cooling performance. They reported their set points as 75 °F for cooling and 65 °F for heating and used their heat pump in an on-off manner. They reported opening windows sometimes during summer afternoons when it got too hot. They did not notice an impact from the through-floor fans installed in the winter of 2013-2014.

Townhome B: Despite the reported comfort issues, the resident still rated satisfaction with heating and cooling as 2 out of 3. All other satisfaction criteria were rated highest. Other key takeaways from the interview were:

- They did not feel well-equipped to operate the house, particularly the space conditioning system.
- Set points were very aggressive: 65 °F for cooling and 78 °F for heating (and yet the heat pump was turned on and off rather than left on).
- Windows were opened for ventilation only a limited amount of time.

4.9 Conclusions for Hudson Passive Townhomes

Unanticipated homeowner behavior negatively impacted comfort and performance. For example, many times the homeowners did not use windows for natural cooling. Thermostat set points reflected a preference for exceptionally warm winter temperatures and cool summer temperatures. Heat pumps were switched on and off manually rather than allowing the system to achieve more even temperatures over time. Under these circumstances, a single point-source for heating and cooling on the first floor was unable to achieve consistent comfort temperatures throughout the year. Adding second heating/cooling point in the form of another ductless mini-split head in the second floor hall may address these issues. While improving comfort, adding a second head may not have a significant impact on energy consumption; given the residents' preference for using the heat pump in an on-off manner, it is likely that the first floor unit would be turned off at night rather than being turned to maximum output in an attempt to condition the second floor as is currently the case.

Certain aspects of the home's design also contributed to excess heat on the second floor. Except for the roof over the entry door, there is no exterior shading on the large southwest facing windows. Windows are European style tilt-turn that open inward and do not have screens. This, along with furnishings and window treatments inhibited window operation. Residents also reported a reluctance to open the southwest windows because of noise from traffic on the Street.

The heat pump is located on the first floor at the bottom of the stairs. In this location, it had difficulty cooling the upstairs bedrooms. Through-floor transfer fans were added to the bedrooms, but were reported by residents to have had little effect, although several were obstructed by furnishings. Upright fans were used in summer, but the bedrooms were sometimes uncomfortably hot. The data did show summer periods with outdoor temperature cooler that second floor temperature, indicating that opening windows could have alleviated some overheating. There was no direct cross ventilation on either floor. On the first floor, cross ventilation could be achieved by opening the rear door, but a lack of screen and security concerns inhibited that approach.

Cooling problems were likely exacerbated by the open stair to the basement that may have served as a repository for cool air from the first floor. Sealing off that opening may prevent cooled air from flowing down to the basement and instead force it up to the second floor.

4.9.1 Energy Consumption

In part due to the judicious use of the heat pumps by the residents, but also at some sacrifice in comfort, both homes used less energy for space conditioning than predicted by REM/Rate and PHPP. Of total energy used, only 12% and 18% were for space conditioning for Townhomes A and B, respectively. DHW accounted for about 40% of energy use in both houses. Plug, lighting, and appliances accounted for the remainder.

5 R-House

The R-House is a 1,225-square-foot, two-story, single-family detached home located in Syracuse, NY. It has a well-insulated building envelope (Table 26) and uses a Zehnder ComfoAir 350 Heat Recovery Ventilator (HRV) to pre-condition air entering the building. The HRV recovers heat from the outgoing air to preheat the incoming air. In addition, a gas-fired water heater with a separate side circuit serves a hot water coil that further heats the incoming ventilation air as the primary space heating system.

The original design called for additional electric resistance heat to be installed as backup, but these heaters were never installed. In the summer of 2011 (after two months of occupancy), the homeowner installed a 1.5-ton Mitsubishi MSZ-FE18NA HyperHeat ductless heat pump to provide supplemental heating and cooling. The single indoor unit was installed in an open area on the second floor to serve the entire house.

Figure 56 shows photos of the house and installed equipment.

Table 26. R-House Specifications

Item	Specification
Slab	R-32 under slab insulation
Basement wall	R-27 insulation
Exterior walls	R-58 dense pack cellulose
Roof	R-68 insulation
Windows and doors	U-factors 0.125 and 0.161 Btu/sf/hr SHGC 0.31 and 0.61
Infiltration	0.44 ACH50
Heating/cooling system	Condensing gas-fired water heater with a separate side circuit that serves a hot water coil that heats incoming ventilation air; 1.5 ton Mitsubishi MSZ-FE18NA HyperHeat Ductless Heat Pump added later
Ventilation system	Zehnder ComfoAir 350 HRV
Water heating	Power vented gas-fired water heater

Figure 56. R-House and its Equipment

(a) House from the Street; (b)Mitsubishi Heat Pump MUZ-FE18NA Installed August 2011; (c) Mitsubishi Heat Pump MUZ-FE18NA Indoor Unit; (d) Space Heating Circuit on Hot Water Tank; (e) Zehnder HRV with HW Heating Coil

5.1 Monitoring Approach

Campbell Scientific CR1000 and CR 206x data loggers were installed along with various sensors and meters to measure system performance and energy use. Further details about the monitoring system are provided in Figure 57. Data were collected at 15-minute intervals starting in November 2010. The data points being collected at R-House ductless heat pump are shown in Figure 57 and Tables 27 and 28. They were selected to measure:

- Induced fan current (FC) to estimate the amount of air (CFM) supplied by the HP indoor unit using correlation developed from experimental data.
- Inlet and outlet air conditions to and from the HP indoor unit (RHR, TARI ,TASI4 and RHS) to calculate the enthalpy difference (HAS-HARI) and thus estimate the cooling or heating load of the heat pump (QC, QH).
- HP energy consumption (WC3) to calculate the performance of the Heat pump in terms of EER and COP.
- TASI1, TASI2 and TASI3 to check the special variation of the supply air from the HP indoor unit; and,
- Compressor current (CC) to track relative compressor power.

Figure 57. Schematic of Ductless Heat Pump with Data Points at R-House

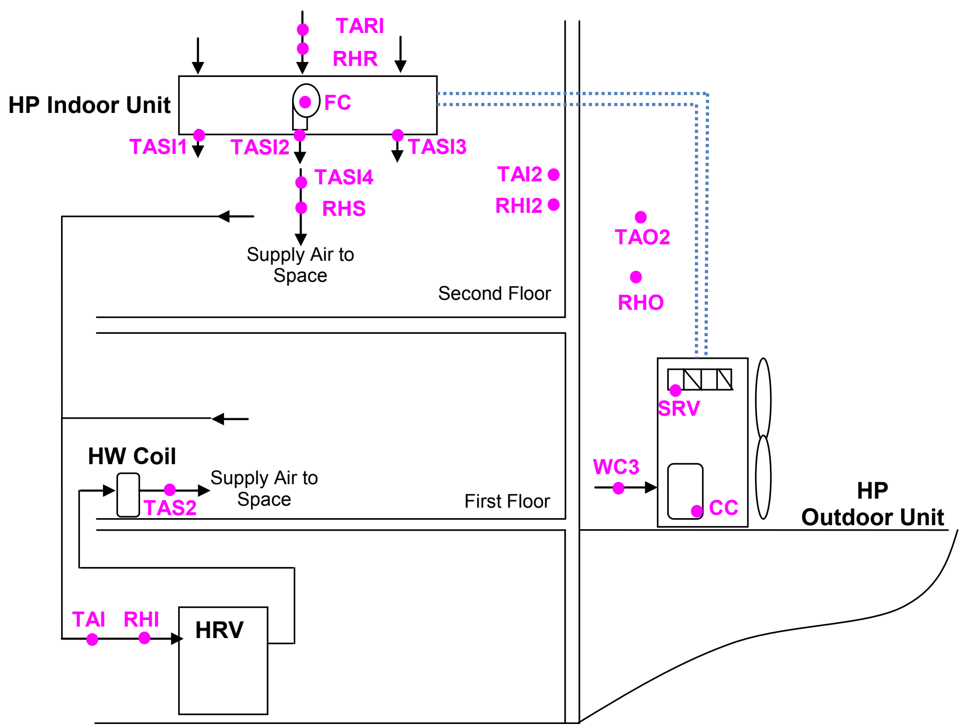


Table 27. R-House Heat Pump Data Points

Data Point	Description	Eng Units	Instrument / Transducer
TASI1	Supply Air Temperature #1	°F	Minco-10k-type2-Thermistor
TASI2	Supply Air Temperature #2	°F	Minco-10k-type2-Thermistor
TASI3	Supply Air Temperature #3	°F	Minco-10k-type2-Thermistor
TASI4	Supply Air Temperature	°F	Vaisala Thermocouple
RHS	Supply Air RH	%	Vaisala RH Transducer
TARI	Return Air Temperature	°F	CS215
RHR	Return Air RH	%	CS215
TAI2	Indoor Temperature Upstairs	°F	4-20 sensor
RHI2	Indoor Space RH (Upstairs)	%	4-20 sensor
TAO2	Outdoor Temperature	°F	Vaisala Thermocouple
RHO	Outdoor RH	%	Vaisala RH Transducer
CC	Compressor Current	amps	Veris 721 Current sensor
FC	ID Fan Current	amps	Veris 721 Current sensor
VF	Fan Speed		Monach
TV	Temperature Vapor Inlet	°F	Minco-10k-type2-Thermistor
SRV	Status Reversing Valve		Veris H300
WC3	Circuit 3 Power	kWh	Wattnode WNB-208-Y-P

Table 28. R-House HRV and Boiler Loop Data Points

Data Point	Description	Eng Units	Instrument / Transducer
FHW	Hot Water Flow Rate	gal	Omega FTB 4607
FG	DHW Tank Gas Use	CF	AM250 Gas Meter with Pulse
WT1	Total House Power (L1)	kWh	Wattnode WYB-208 (P1)
WT2	Total House Power (L2)	kWh	Wattnode WYB-208 (P2)
WM	Mechanical System Power	kWh	Wattnode WYB-208 (P3)
WC1	Circuit 1 Power	kWh	Wattnode WYB-208 (P1)
WC2	Circuit 2 Power	kWh	Wattnode WYB-208 (P2)
WC3	Circuit 3 Power	min	Wattnode WYB-208 (P3)
SP2	Hot Water Coil Pump Status	min	Veris 800 Current Switch
IFV	HRV Fan Current (dmpr pos)	amps	Veris 921 Current Sensor
TAS	HRV Supply Temperature	°F	Type-T Thermocouple
TAS2	Supply Temperature (after HW Coil)	°F	Type-T Thermocouple
TWS	Temperature to HW Coil	°F	Type-T Thermocouple
TWR	Temperature from HW Coil	°F	Type-T Thermocouple
RHR	Space RH (in HRV)	%	Vaisala RH Transducer
TAO	Outdoor Temperature (in HRV)	°F	Type-T Thermocouple
TAI	Space Temp (in HRV)	°F	Type-T Thermocouple
THWO	DHW Outlet Temperature	°F	Type-T Thermocouple
THWI	DHW Inlet Temperature	°F	Type-T Thermocouple
TCWI	Cold Water into Preheat Tank	°F	Type-T Thermocouple

Figure 58, Figure 59, and Figure 60 show the monitoring equipment installed at R-house. The use of wireless equipment minimized the need to run wires within the living space.

Figure 58. Monitoring Equipment and Wireless Datalogger for Outdoor Heat Pump Unit at R-House

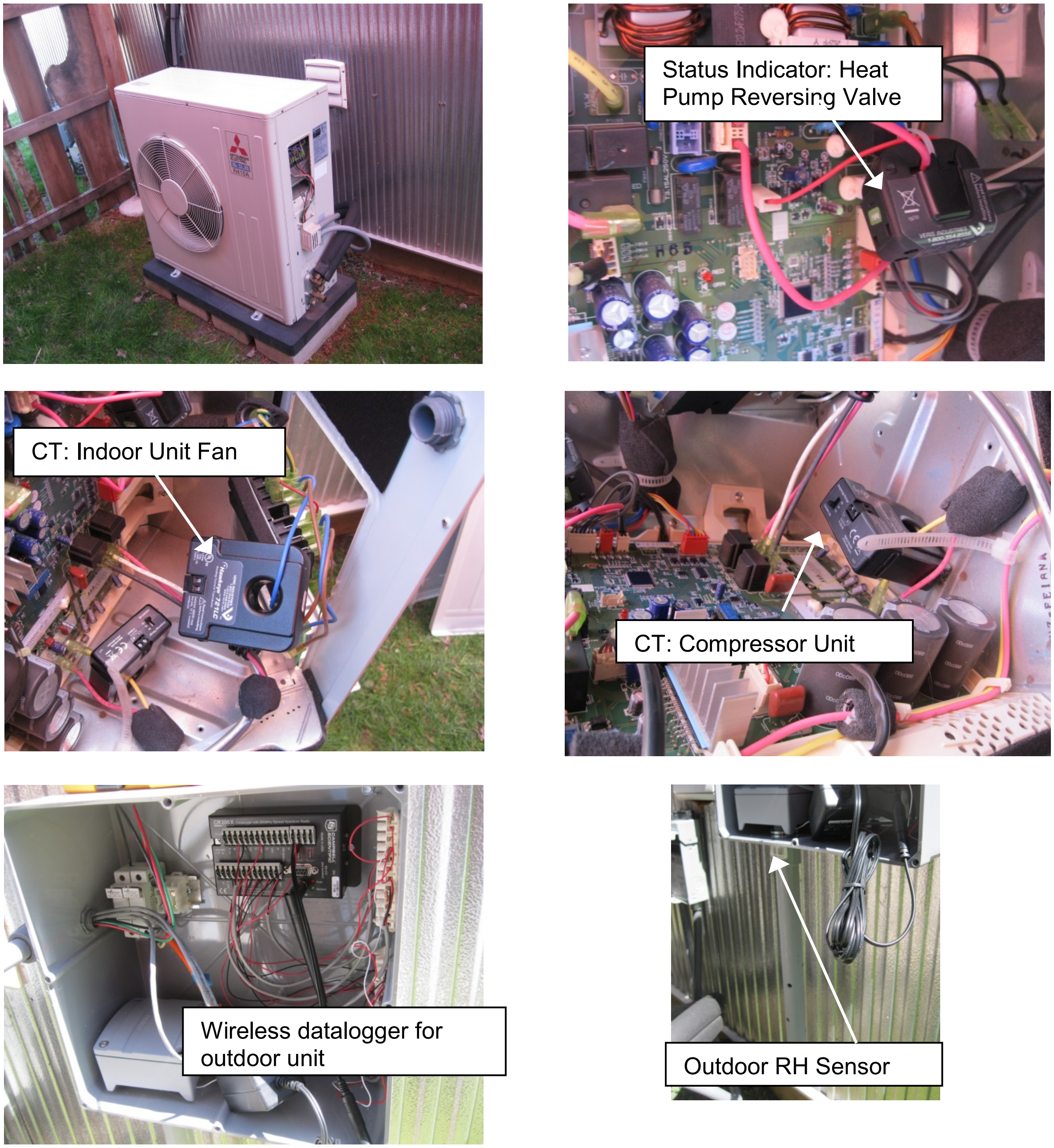


Figure 59. Current Transducers, Gas Meter Sensor, Wattnode Meter, Make Up Water Flow Sensor for DHW, and Main Datalogging System at R-House

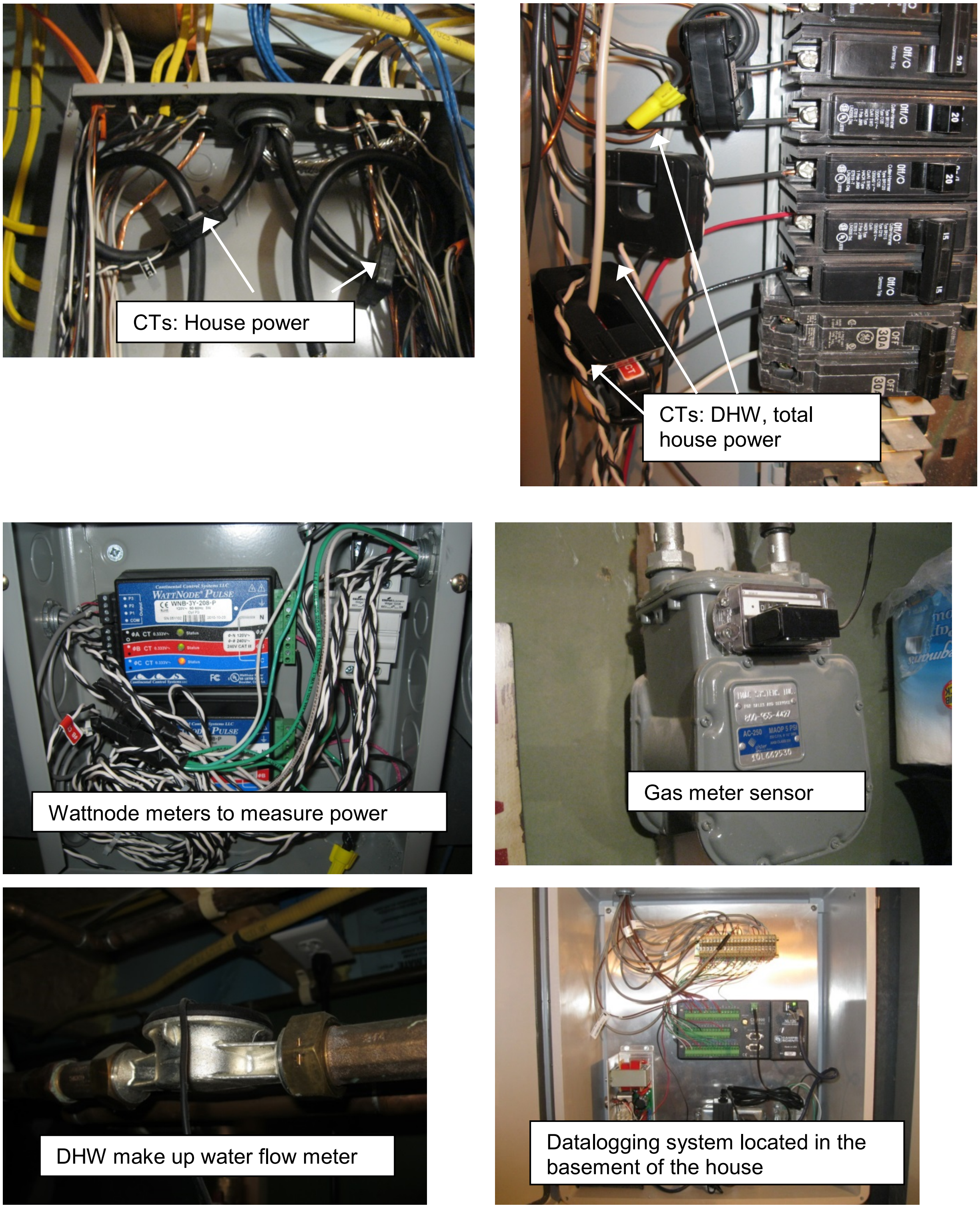
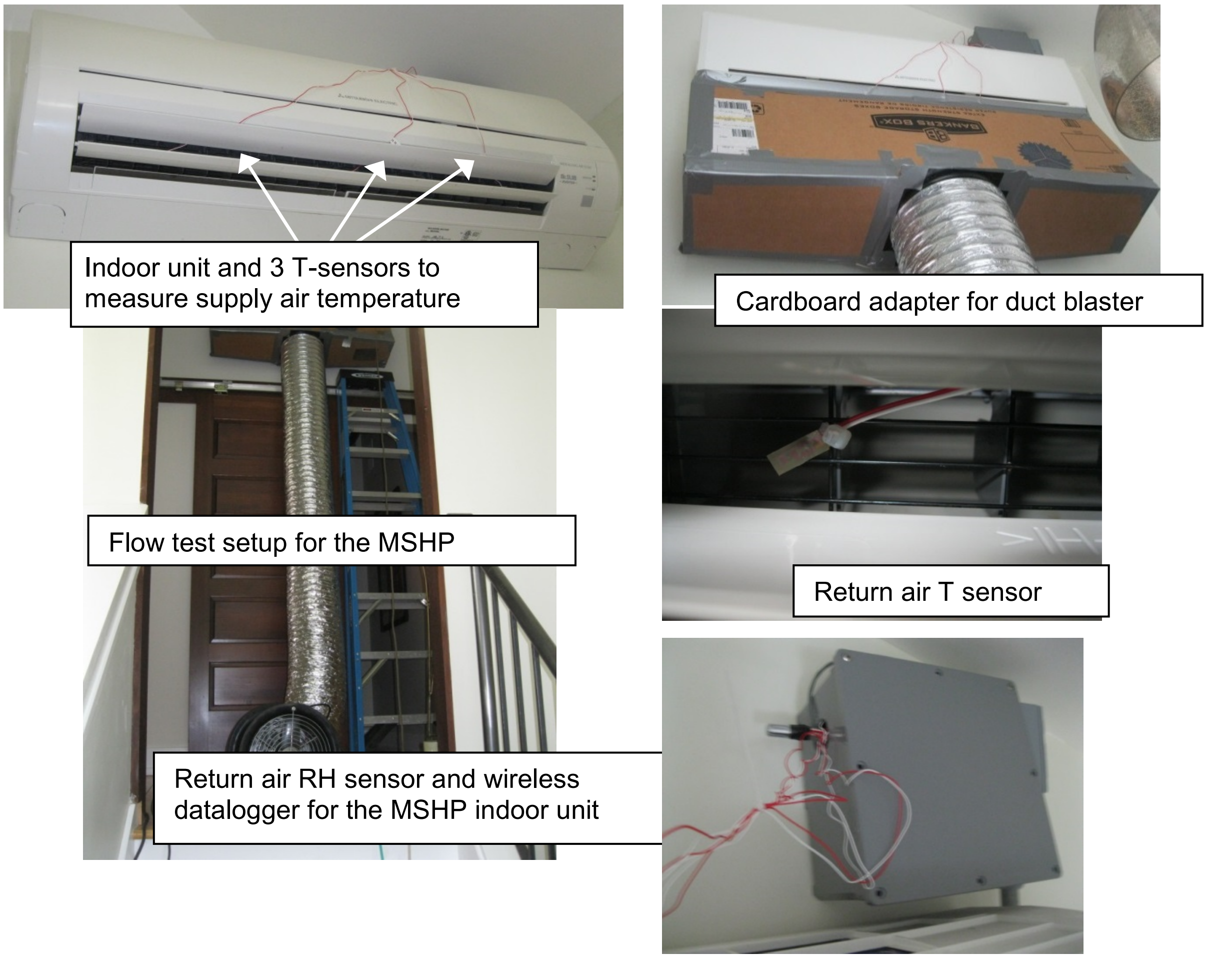


Figure 60. Flow Test Setup for the MSHP and Various Sensors to Monitor MSHP Performance at R-House



5.2 Measured Results

5.2.1 Monthly Energy Use and Loads

Table 29 summarizes the monthly energy use and loads from November 2010 through April 2014. Electric use was measured for the total house and boiler draft fan. Electric use for the heat pump was measured starting in late February 2012. (The heat pump was installed in July 2011).

The annual periods for 2012 and 2013 totaled at the bottom of the table were shifted by two months to include 12 months of heat pump power. Gas use was measured for the water heater. Hot water use was measured for the entire period. The thermal energy supplied to the ERV for space heating and delivered by the hot water tank for domestic water heating are also shown in Table 29. Dividing the sum of the space and water heating Btu by the total therms consumed (converted to Btu) yields an average efficiency of 70% over the entire period. This is in line with the expected efficiency of a power-vented water heater.

Note that ERV heating use and gas use is artificially inflated for May and June 2013 because a valve was left open on the heating loop during those two months. The design of the heating system incorporated a hot water coil in the HRV supply air duct. It was found that this resulted in a thermosyphon continuously moving 5-10% of the design flow through the coil, even when there was no call for heat. This small flow delivered a disproportionally large amount of heat to the home resulting in unnecessary energy use and overheating. A check valve could have prevented this waste (CDH Energy Corp 2013). To halt the thermosyphon phenomenon, a ball valve had to be manually closed each season. This design flaw required the occupant to close the valve when heating was no longer required, something they did not always remember to do.

Table 29. Monthly R- House Energy Use, Water Use, and Heating Loads

	Total (kWh)	Boiler System Use (kWh)	ERV Space Heating (MBtu)	Water Heating (MBtu)	Hot Water Use (gal/day)	Boiler Gas Use (therms)	Heat Pump Use (kWh)
Nov-10	291	7	-	416	29	12	
Dec-10	718	41	-	701	45	29	
Jan-11	580	77	-	985	53	40	
Feb-11	493	56	1,588	1,129	58	45	
Mar-11	396	20	2,372	1,043	49	52	
Apr-11	328	19	1,721	826	44	38	
May-11	230	16	2,134	735	39	41	
Jun-11	212	11	2,381	539	36	27	
Jul-11	357	9	967	432	31	19	
Aug-11	376	7	6	472	35	13	
Sep-11	301	7	14	520	37	13	
Oct-11	266	11	15	521	33	13	
Nov-11	298	52	1	684	40	15	
Dec-11	447	73	6	851	43	18	
Jan-12	569	48	1,570	1,213	58	32	
Feb-12	322	18	2,199	1,465	74	49	0
Mar-12	400	19	1,927	1,563	76	53	71
Apr-12	332	18	1,850	1,489	77	50	17
May-12	486	16	708	1,158	69	28	159
Jun-12	418	7	3	686	49	13	154
Jul-12	429	5	1	396	32	9	193
Aug-12	409	5	2	352	30	8	186
Sep-12	391	6	9	471	38	10	141
Oct-12	297	9	1,473	626	42	18	45
Nov-12	371	15	1,940	735	46	22	34

Table 29 continued

	Total (kWh)	Boiler System Use (kWh)	ERV Space Heating (MBtu)	Water Heating (MBtu)	Hot Water Use (gal/day)	Boiler Gas Use (therms)	Heat Pump Use (kWh)
Dec-12	505	47	1,893	577	32	26	52
Jan-13	517	44	2,287	934	45	38	68
Feb-13	362	47	2,085	935	49	35	26
Mar-13	345	25	2,228	856	40	39	8
Apr-13	300	15	2,138	1,008	51	39	3
May-13	461	14	2,081	826	44	36	191
Jun-13	496	11	1,309	582	36	24	209
Jul-13	579	7	-	538	37	13	297
Aug-13	537	7	0	568	40	14	278
Sep-13	565	8	1	612	44	14	239
Oct-13	503	9	1	853	54	18	163
Nov-13	505	17	705	1,181	66	28	103
Dec-13	673	24	2,161	1,171	57	41	152
Jan-14	554	43	2,616	1,059	49	43	98
Feb-14	367	38	2,082	891	45	37	38
Mar-14	360	36	2,166	1,095	50	41	14
Apr-14	388	40	414	1,043	52	25	39
Annual 2011	4,283	357	11,204	8,736	41	333	-
Annual 2012	4,917	236	14,177	9,921	49	309	1,146
Annual 2013	5,885	215	15,322	10,142	47	345	1,778

5.3 Heat Pump Performance

For the heat pump, the heat rejected into (heating operation) and extracted from (cooling operation) the conditioned space are calculated using the enthalpy difference and air flow as shown in Equation 9 and Equation 10:

$$Q_c = cfm\ x\ 60\ x\ 0.075 * (h_{ari} - h_{as})/1000 \quad (9)$$

$$Q_h = cfm\ x\ 60\ x\ 0.075x\ C_p x\ (TASI4 - TARI)/1000 \quad (10)$$

where:

- Qc = Cooling load (MBtu/h)
- Qh = Heating load (MBtu/h)
- cfm = Supply air flow (cfm)
- h_{ari} = Return air enthalpy (Btu/lb), hari = f(TARI,RHR)
- has = Supply air enthalpy (Btu/lb), has = f(TASI4,RHS)
- TARI = Return air temperature (°F)
- TASI4 = Supply air temperature (°F)
- Cp = Specific heat of air (Btu/lb °F), 0.24 at STP

Experimental correlations between fan current and a combination of one-time supply air flow (cfm) measurements and manufacturers catalog data were used to estimate the flow in different operating conditions. Figure 61 shows the correlation used and cubic function gives best fit to the data.

Figure 61. Air Flow vs. Fan Current for HP Indoor Unit at R-House

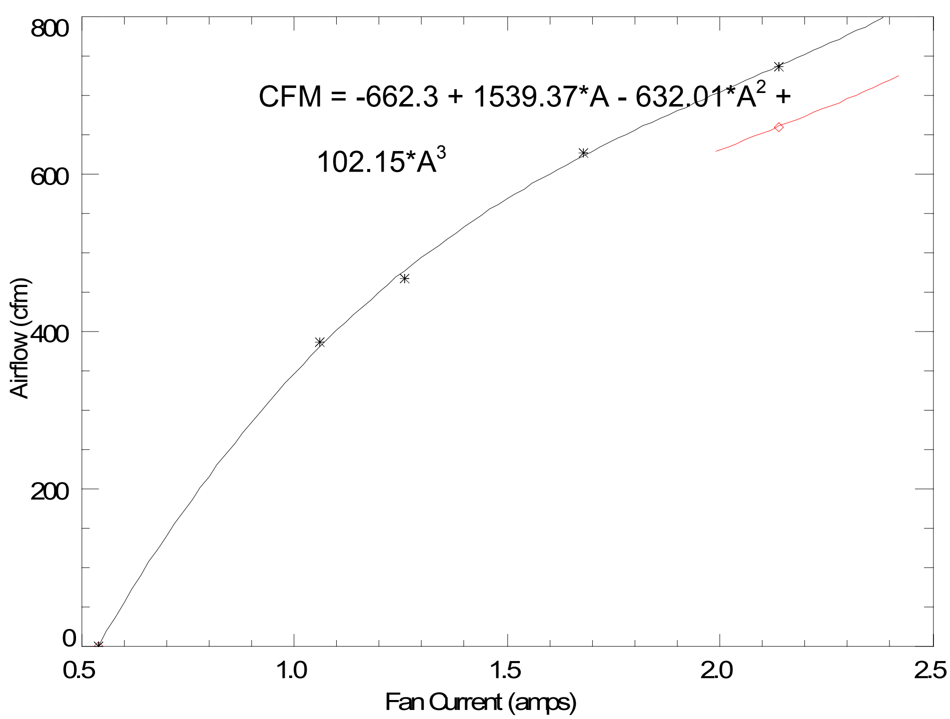


Table 30 summarizes the energy usage, performance and heating/cooling load of the heat pump over the course of the twelve month monitoring period when heat pump measurements were obtained (May 2013 through April 2014). Most of the variations in electricity are due to seasonal temperature swings. Full heat pump temperature and relative humidity measurements started in August 2013, when the CS215 T/RH probes were installed. Performance analysis is done for data after this date.

The performance of the heat pump during heating is measured in Coefficient of Performance (COPh) and it is calculated with Equation 11:

$$COP_h = Q_{t,h} /(WC3 \ x \ 4 \ x \ 3.413) \quad (11)$$

where:

- Q t,h = Heat pump Heating load (MBtu/h)
- WC3 = Heat pump power consumption (kWh)

The performance of the heat pump during cooling is measured in Energy Efficiency Ratio (EERc) and it is calculated with Equation 12:

$$EER_c = Q_{t,c} /(WC3 \ x \ 4) \quad (12)$$

where:

- Q t,c = Heat pump cooling load (MBtu/h)
- WC3 = Heat pump power consumption (kWh)

The average heating COP was calculated to be 1.7 and cooling EER 24.2.

Table 30. Monthly R-House Heat Pump Energy Use, Heating/Cooling Loads and Performance Data

Green data is defrost operation.

		Heating				Cooling			
Month	Ambient Temp. (°F)	Runtime (hrs)	Load (MBtu)	HP Energy (kWh)	COP	Runtime (hrs)	Load (MBtu)	HP Energy (kWh)	EER (Btu/Wh)
May-13	64.9	-	-	-	-	234.9	-	190.6	-
Jun-13	69.1	-	-	-	-	284.9	-	208.8	-
Jul-13	76.0	-	-	-	-	487.7	-	296.7	-
Aug-13	71.6	-	-	-	-	581.8	7,404.8	278.1	26.6
Sep-13	64.3	-	-	-	-	504.6	6,316.4	239.4	26.4
Oct-13	56.2	8.8	38.7	4.4	2.6	364.9	3,053.8	158.7	19.2
Nov-13	42.0	134.8	489.4	79.3	1.8	35.3	415.0	23.3	17.8
Dec-13	33.6	239.7	725.4	146.9	1.4	8.7	5.7	5.1	-
Jan-14	25.9	121.8	548.0	93.7	1.7	7.2	5.8	4.1	-
Feb-14	28.1	53.3	222.9	37.1	1.8	2.4	0.8	1.2	-
Mar-14	32.7	17.6	94.6	13.1	2.1	0.8	0.3	0.4	-
Apr-14	50.5	-	-	-	-	69.5	663.4	39.2	16.9
Total		575.9	2,119.1	374.4	1.7	2,582.7	17,866.0	1,445.6	24.2

5.3.1 Typical Cooling Day Results

Figure 62 through Figure 65 indicate the temperature trend and heat pump performance for a typical cooling day. The performance of the heat pump during cooing is measured in Energy Efficiency Ratio (EERc) and it is calculated as with Equation 13:

$$EER_c = Q_{t,c} / (WC3 \times 4) \qquad (13)$$

where:

- Qt,c = Heat pump cooling load (MBtu/h)
- WC3 = Heat pump power consumption (kWh)

Figure 62. Space Condition and Heat Pump Operation for a Typical Cooling Day at R-House

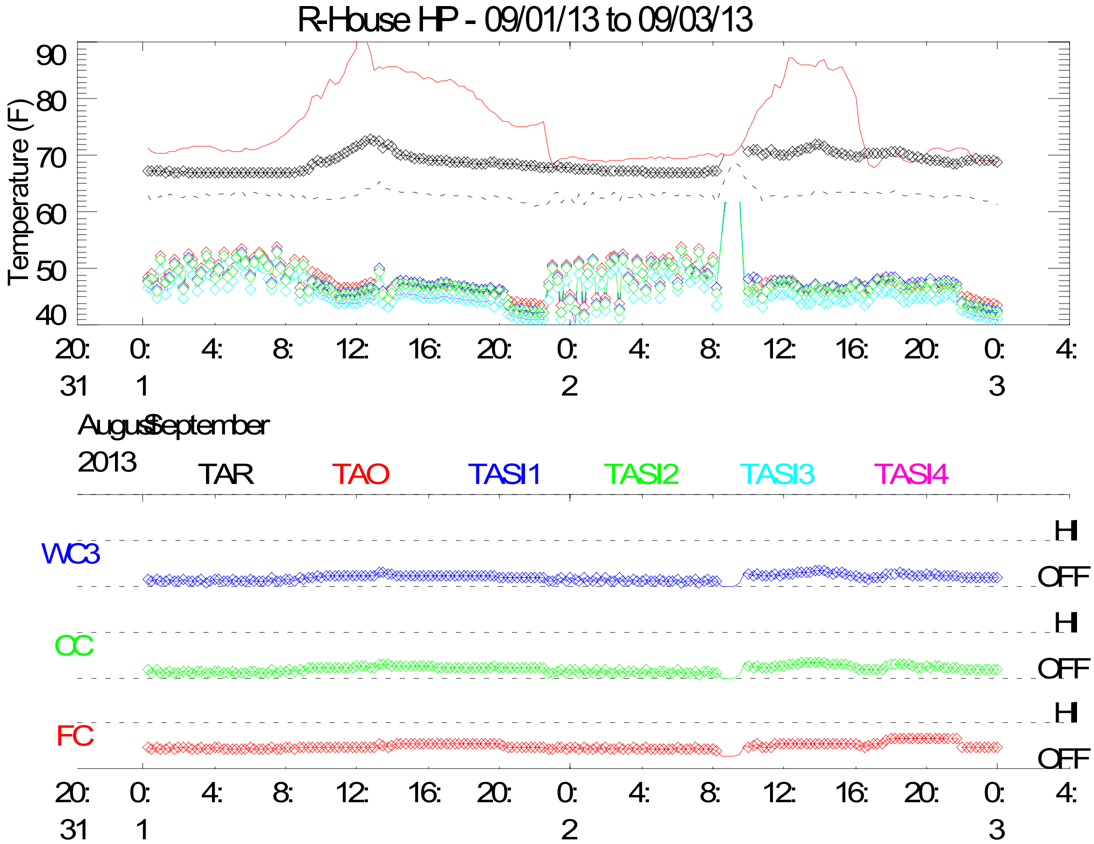


Figure 63. Heat Pump Performance for a Typical Cooling Day at R-House

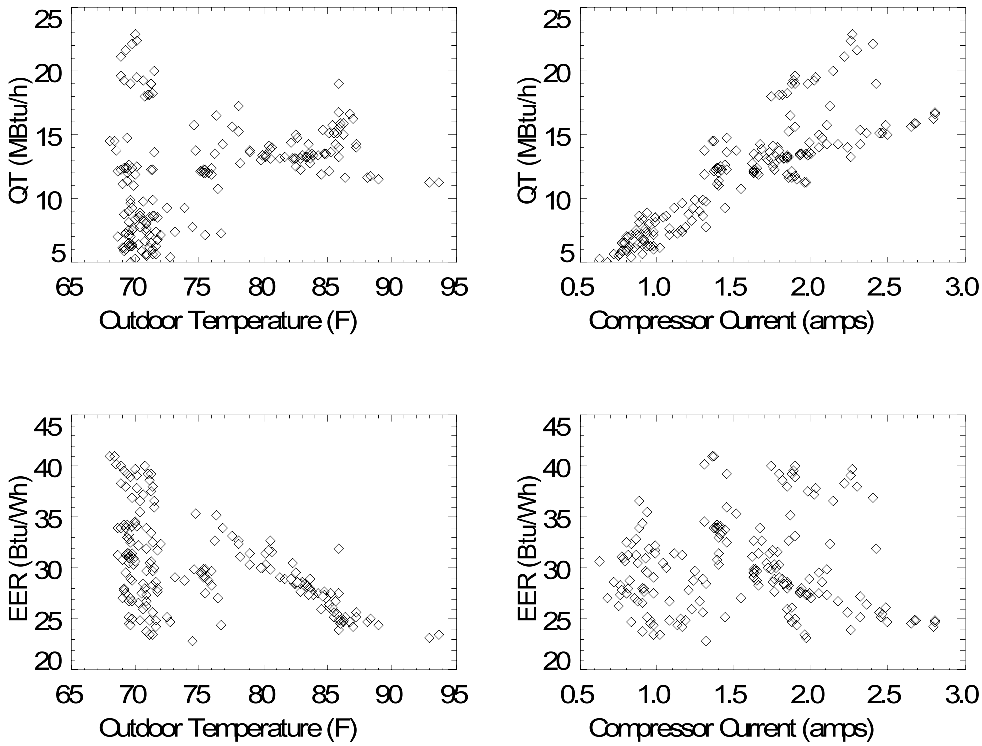


Figure 64. Typical Cooling Day Space Condition on the Psychometric Chart at R-House

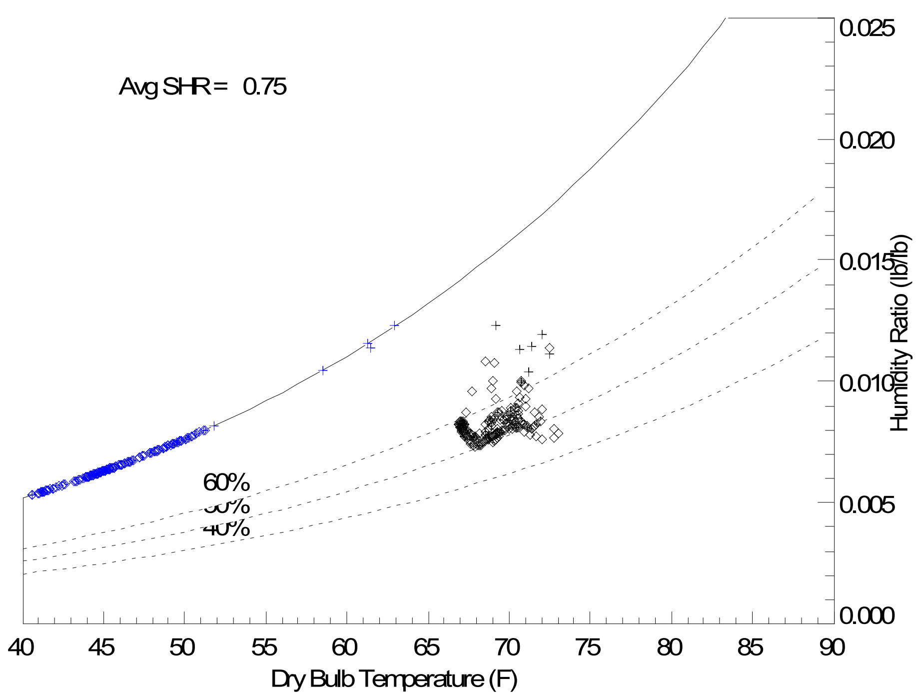
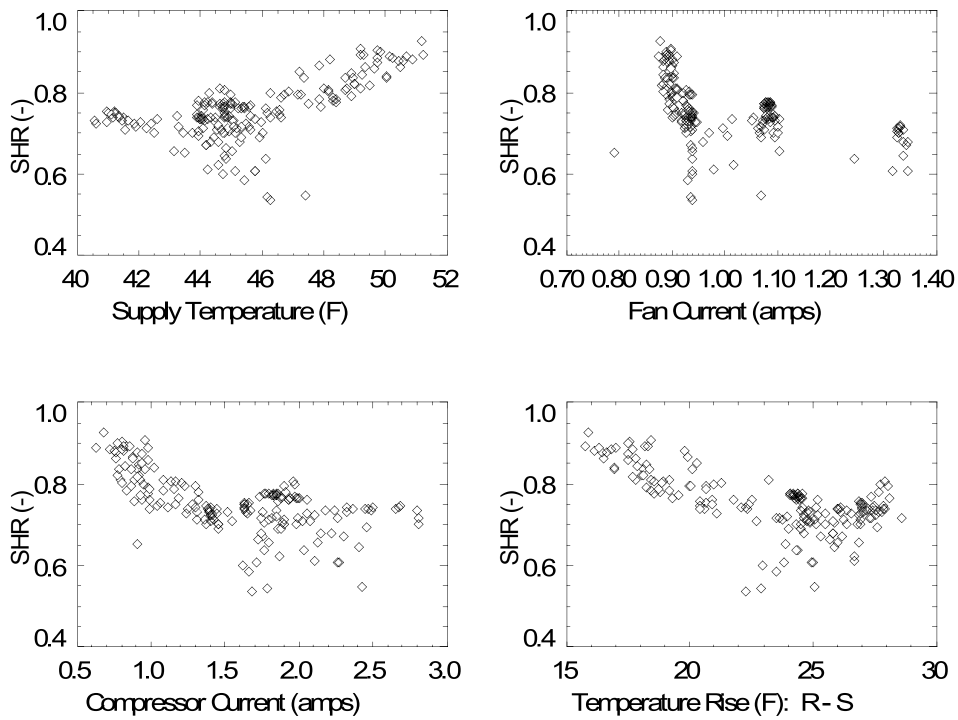


Figure 65. Room Sensible Heat Ratio (SHR) for a Typical Cooling Day at R-House



5.3.2 Typical Heating Day Results

Figure 66 through Figure 68 indicate the temperature trend and heat pump performance for a typical heating day. The performance of the heat pump during heating is measured in Coefficient of Performance (COPh), and it is calculated with Equation 14:

$$COP_h = Q_{t,h} / (WC3 \times 4 \times 3.413) \quad (14)$$

where:

- Qt,h = Heat pump heating load (MBtu/h)
- WC3 = Heat pump power consumption (kWh)

Figure 66. Space Condition and Heat Pump Operation for a Typical Heating Day at R-House

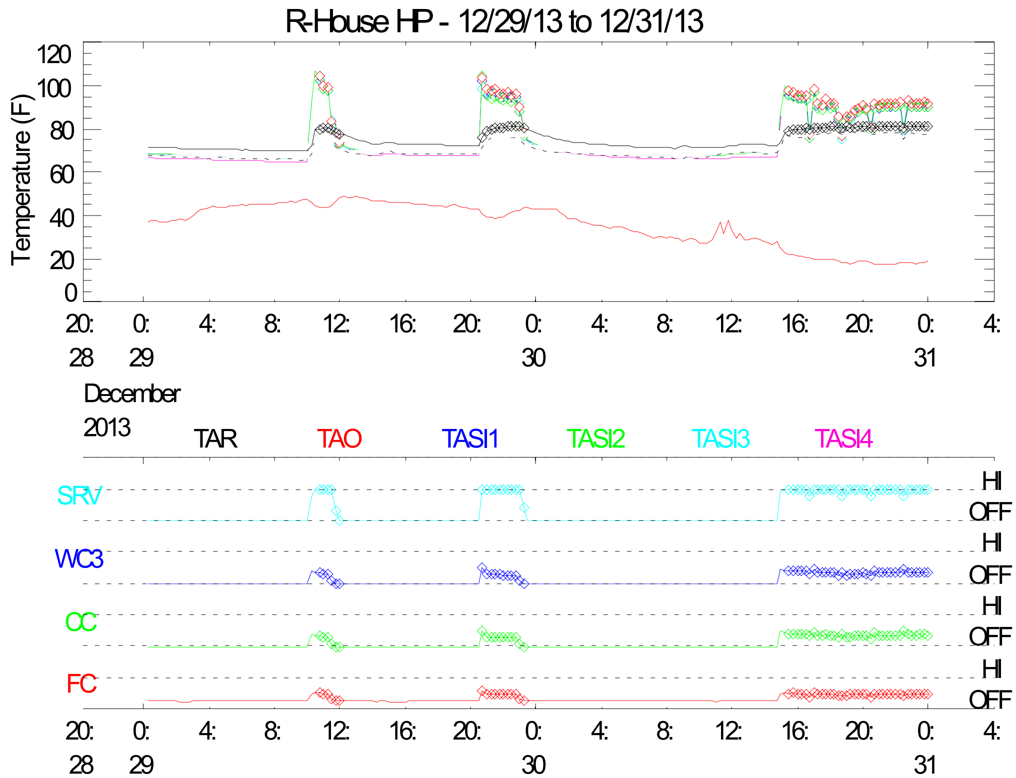


Figure 67. Heat Pump Operation Trends during Defrosting at R-House

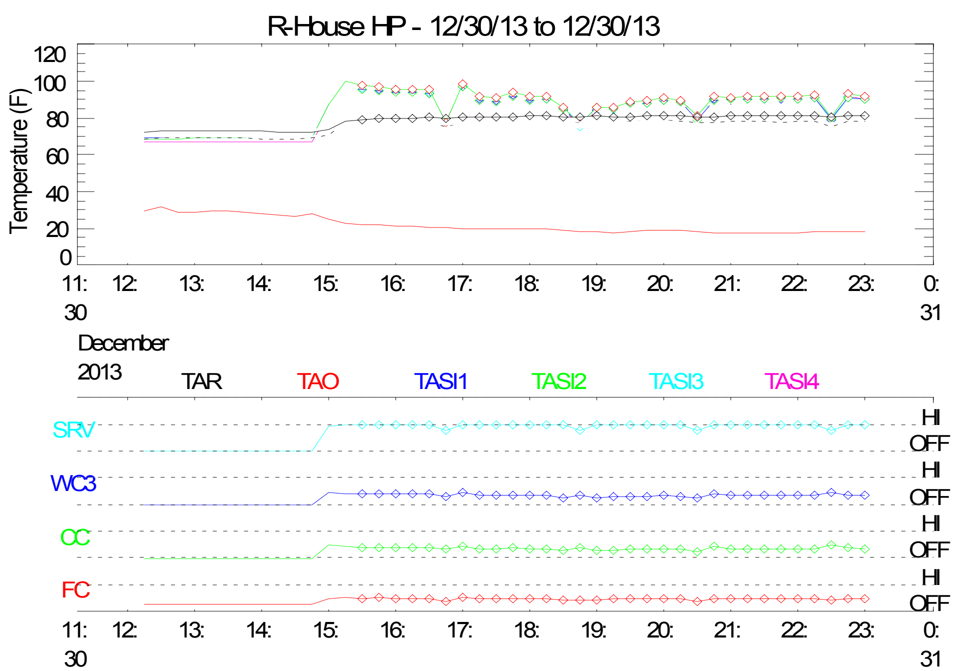
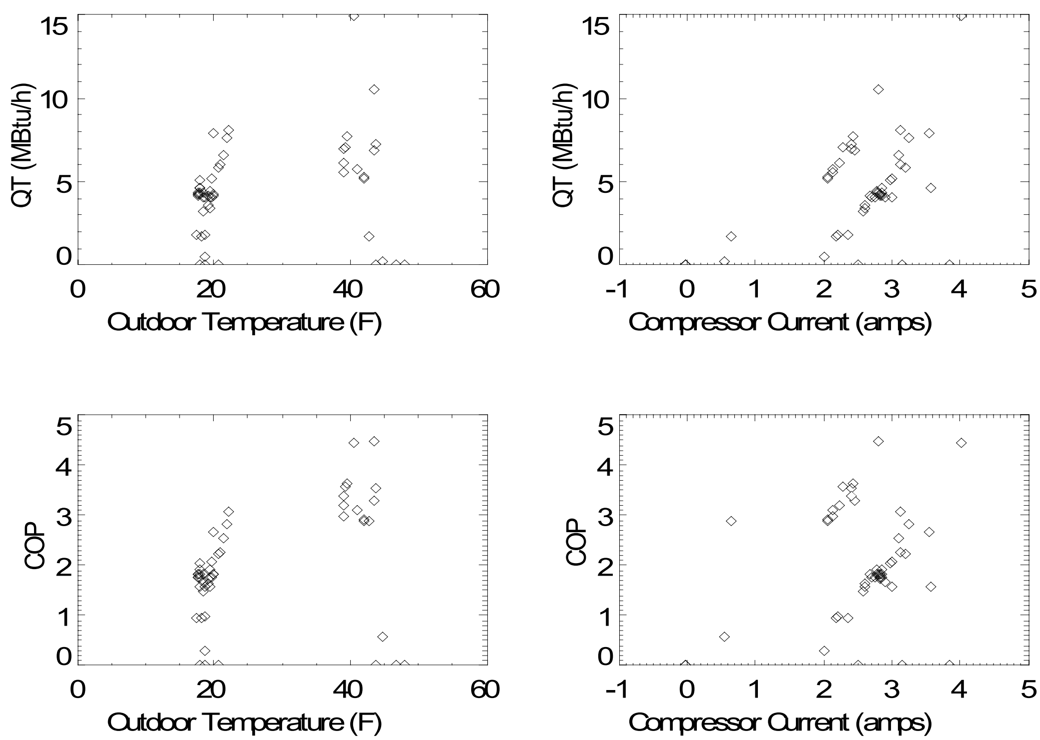


Figure 68. Heat Pump Performance for a Typical Heating Day at R-House



5.3.3 Space Heating and Cooling Trends

Figure 69 shows the calculated heat pump and hot water heating coil load for the monitoring period. The cooling load was stable around 15 MBtu/h. For the heating period, the operation of the heat pump was intermittent and the majority of the house heating was coming from the hot water heating coil. The hot water heating coil was supplying a nearly constant heating of around 3 MBtu/h while the heating from the heat pump varied between 2 MBtu/h and 14 MBtu/h.

Figure 69. Heating and Cooling Loads for R-House

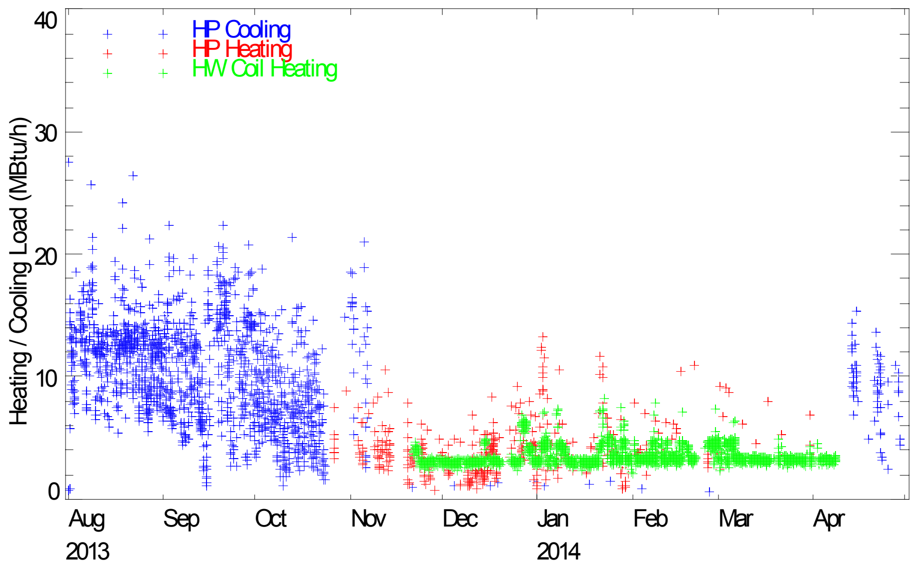


Figure 70 and Figure 71 shows the trend of measured space heating and cooling loads with ambient temperature on a daily basis, a trend often referred to as the heating load line. The figures show that except for a very low outdoor temperature (i.e., outdoor temperature less than 20 °F), the heating load was nearly constant and independent of the outdoor temperature while there was a sharp increment in cooling load with a small increment in outdoor temperature.

Figure 70. Heating and Cooling Loads vs. Outdoor Temperature (R-House)

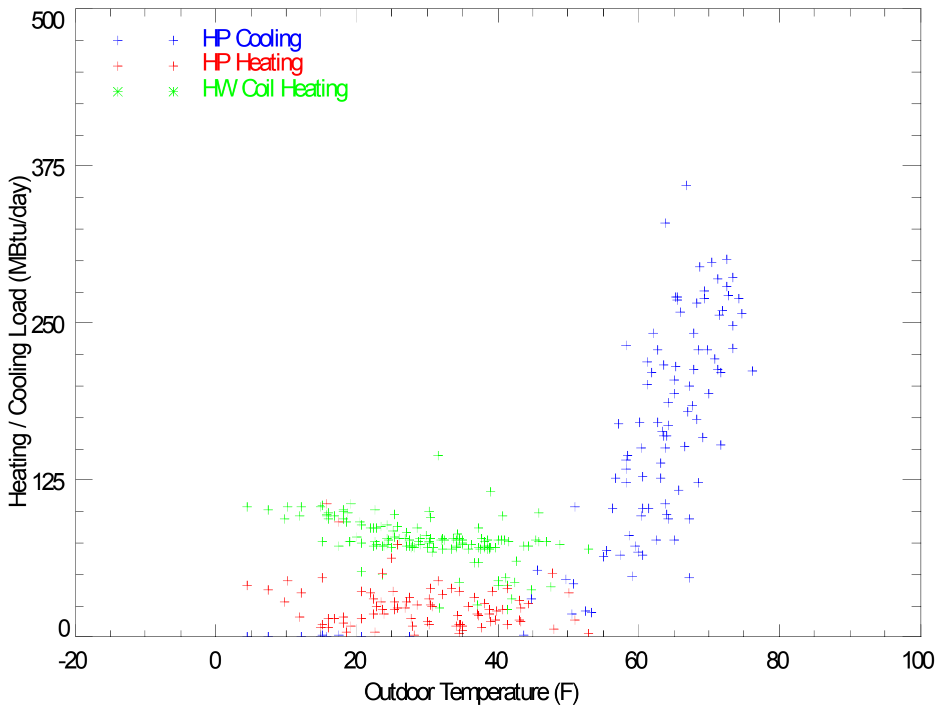
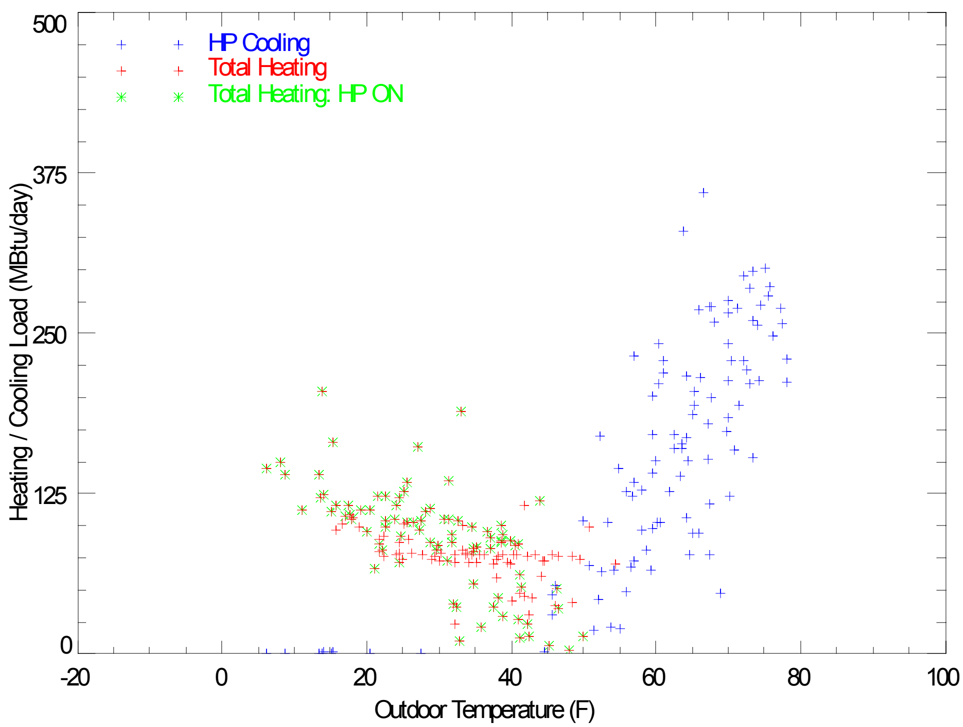


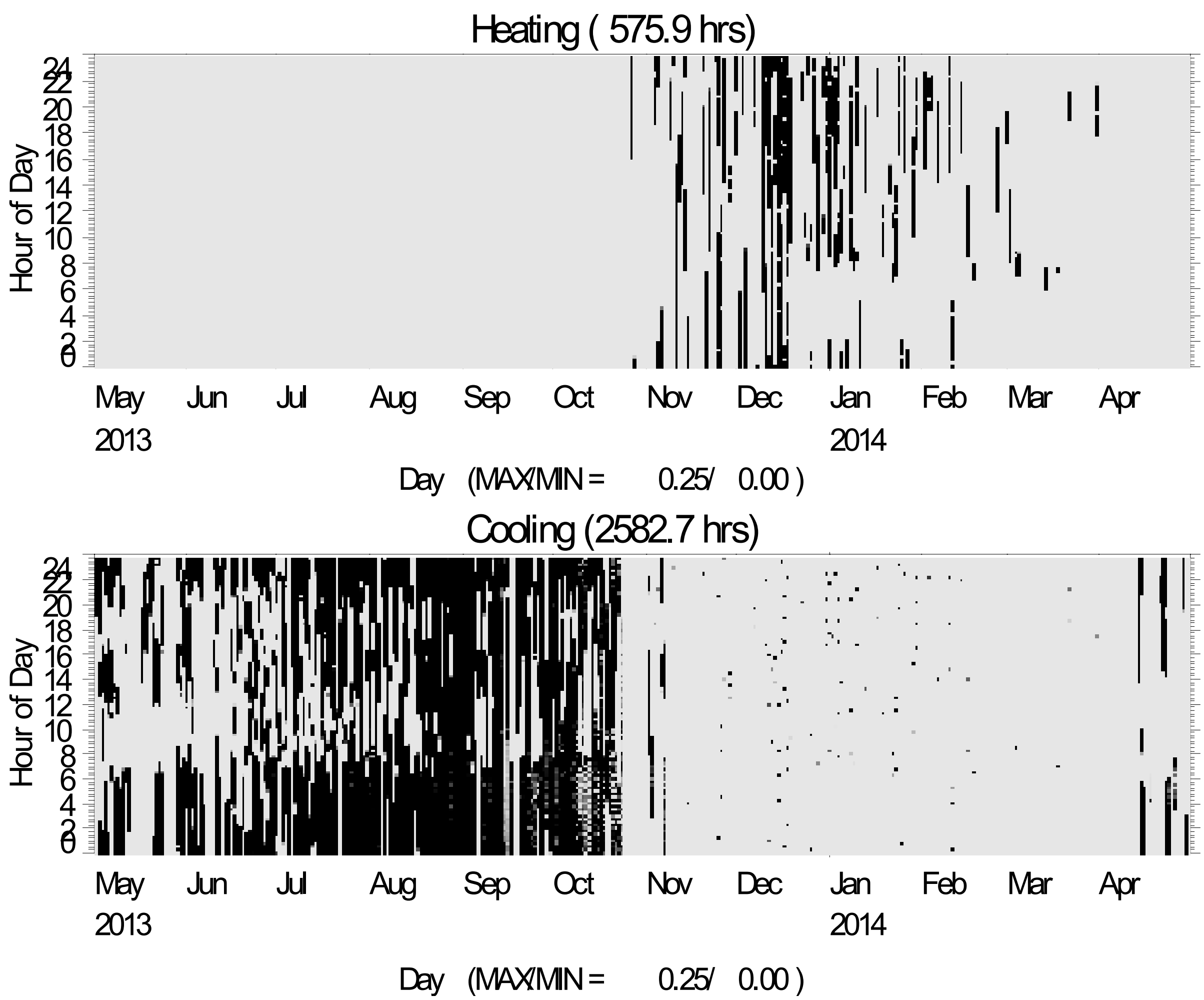
Figure 71. Total Heating and Cooling Loads vs. Outdoor Temperature (R-House)



The shade plots of runtime displayed in Figure 72 show the operating patterns for cooling and heating operation of the heat pump. The days of the year are shown on the x-axis and the hour of the day is shown on the y-axis. Each day is represented by a vertical stripe of 96 fifteen-minute data records. Heat pump run time in each period is represented by varying shades of gray. Intervals with higher runtimes are represented by darker shades of gray, and intervals of lower runtimes are represented by light shades of gray.

The shade plot for the heating operation shows that the heating pattern of the heat pump was random and the heat pump was in heating mode for a total of 575.9 hrs during the one-year monitoring period. The shade plot for cooling operation shows that cooling was needed from May to mid-October. The intermittent black dots during the winter are defrost operation.

Figure 72. Shade Plots for Heating and Cooling Operations



5.3.4 Indoor Space Conditions and Supply Air Trends

The upstairs indoor condition of the R-House, where the indoor unit of the ductless heat pump is located, was monitored. Figure 73 shows the heat pump supply and return air temperatures across the nine-month monitoring period, the period where heat pump supply air temperature was available. The average supply temperature was 57.7 °F with minimum supply temperature around 45 °F for the cooling period. During heating season, the heat pump was not used frequently and a supply temperature as high as 120°F was observed during its operation (the heat pump was used intermittently). For the same period, the supply airflow rate from the heat pump (Figure 74) was observed to reach as high as 637 cfm. For most of the operation period, the flow was in the range of 200 cfm to 400 cfm.

Figure 73. R-House Heat Pump Supply and Return Temperatures Trend

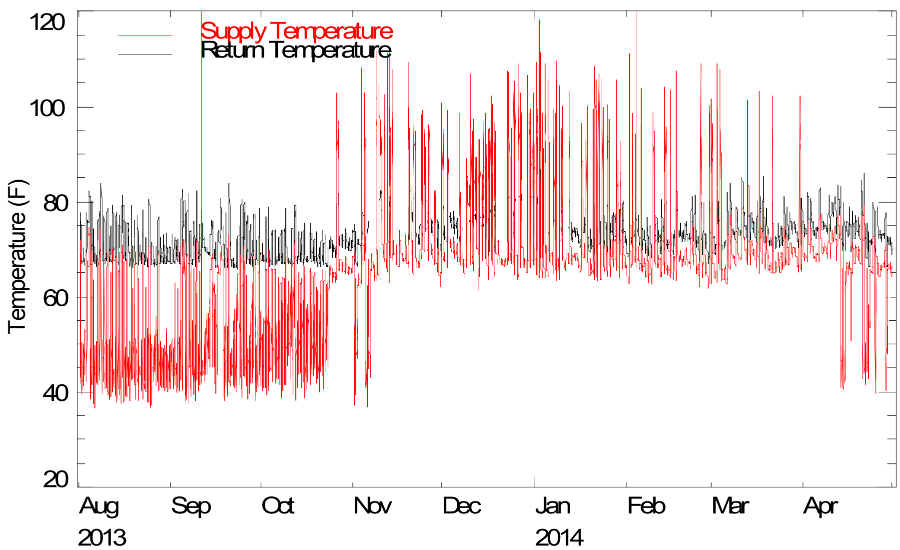


Figure 74. Heat Pump Supply Air Flow for R-House

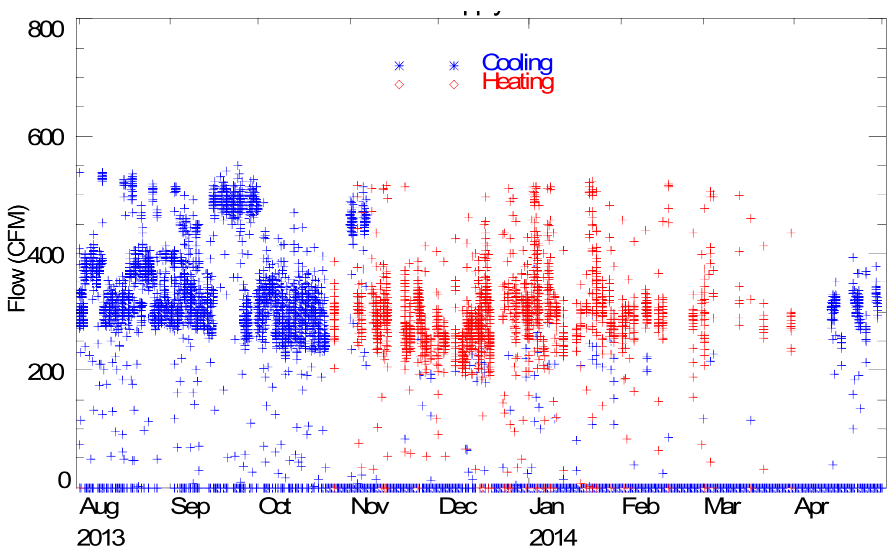


Figure 75 shows the second-floor space air temperature and the mixed air temperature at the inlet of the HRV. The corresponding hot water coil supply temperature in the same plot shows that there was artificial heating from May to mid-June due to unclosed heating coil valve. The HRV supply temperature was reduced after mid-June after the heating coil valve was closed.

Figure 75. Space Air and HW Coil Supply Air Temperature Trends for R-House

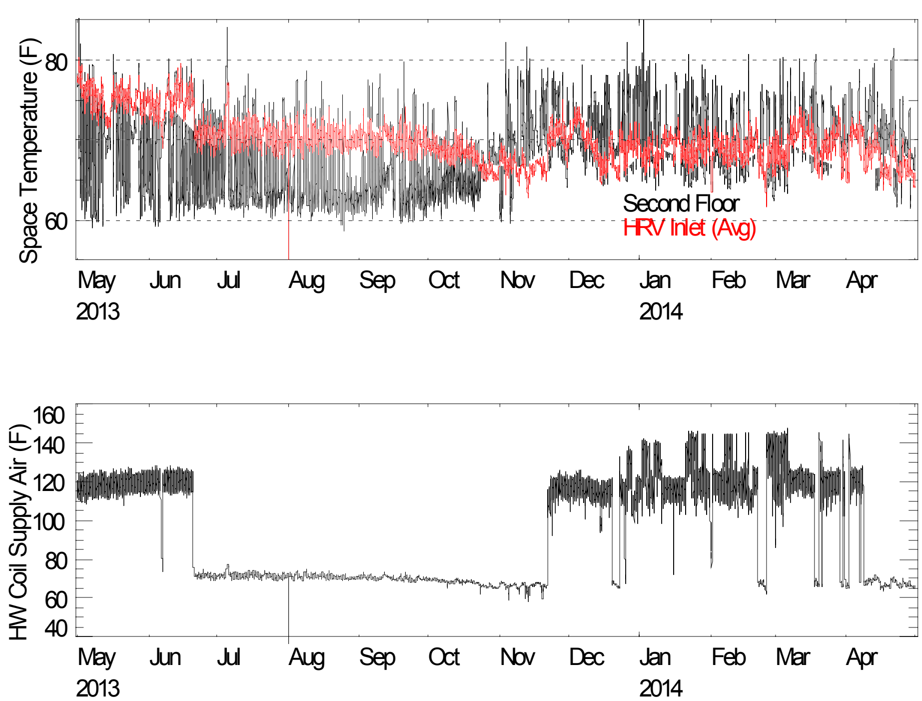


Figure 76 and Figure 77 show the temperature and humidity conditions on the psychrometric chart during heating and cooling, respectively. It indicates that the occupants used the heat pump intermittently.

Figure 76. Daily Conditions Shown on the Psychrometric Chart during Heating at R-House

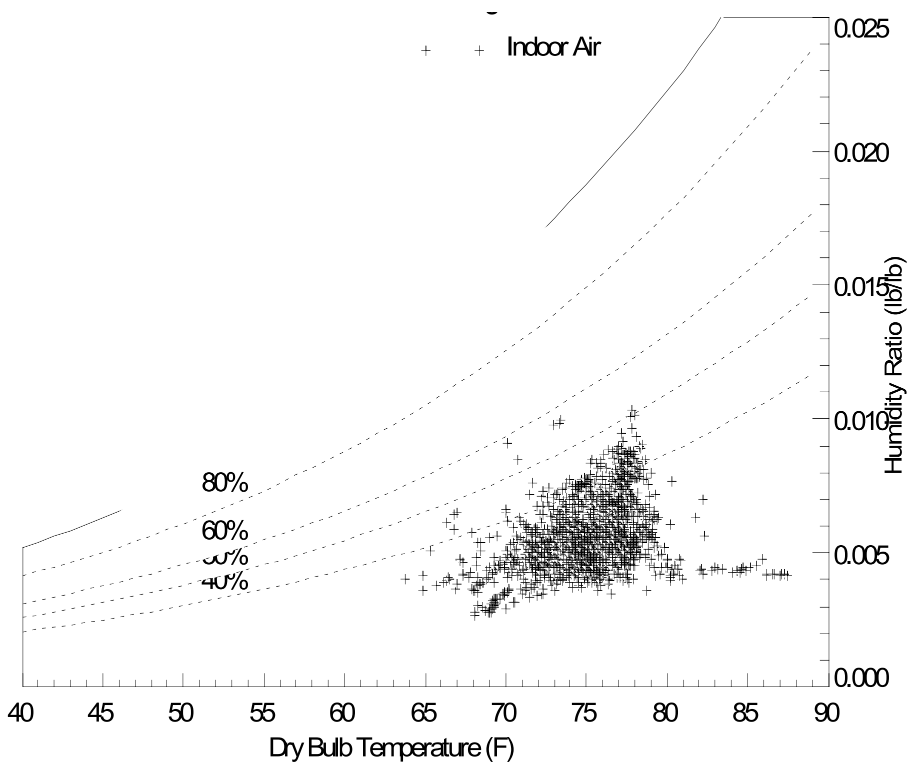
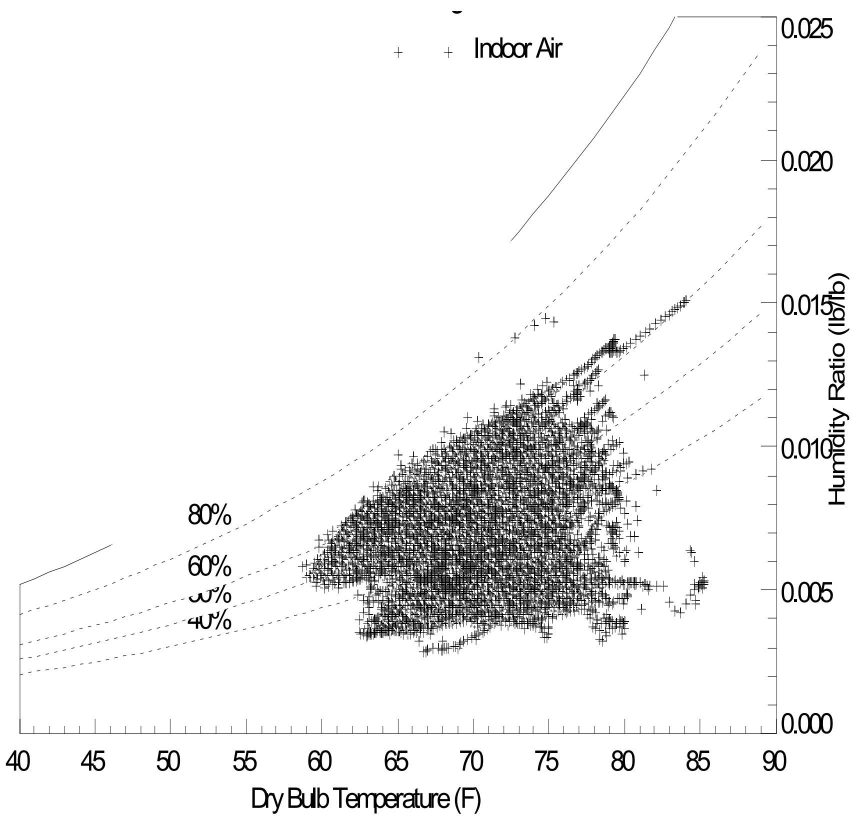


Figure 77. Daily Conditions Shown on the Psychrometric Chart during Cooling at R-House



There were two indoor space temperature sensors: one measuring average indoor temperature inside the HRV return duct and another measuring space temperature on the second floor. In addition, there was a relative humidity sensor on the second floor. Table 31 provides some comfort metrics, comparing periods before and after the installation of the heat pump (approximately February 2012). During heating season, the average indoor space temperature was about 70 °F, however there were many cooler hours. According to the homeowner, they did not set back the space heating system thermostat set point (it was left at 70°F), but they do prefer cool bedrooms at night and sometimes opened a window during winter nights. Therefore, the most likely explanation for these cool winter hours were that the space heating system could not reach setpoint, possibly due to the limited HRV airflow (at medium fan speed setting on the HRV) and an open window. The percent of hours with a temperature spread between floors of more than 4 ºF increased sharply after the heat pump was installed, perhaps indicating some use of the heat pump for upstairs heating. A temperature of 72 °F was selected as a winter season overheating threshold. Overall, the average indoor temperature exceeded this threshold 18% of the time, indicating that there was some overheating possibly due to solar gain.

During cooling season, the average temperature was 76 °F before the installation of the heat pump, when there was no cooling system, and 72 °F after. The percent of hours with space temperature above 78 °F (especially on the second floor) was quite high before the heat pump was installed. Once the heat pump was installed, the number of hours with uncomfortably warm temperatures dropped to less than 2% overall and less than 10% on the second floor. The remaining hours include time when the heat pump was off by choice (i.e., when the home was unoccupied).

Relative humidity over 60% can be perceived as uncomfortable. The percent of time with relative humidity over 60% declined from about 5% to about 3% with the installation of the heat pump. Generally humidity control was very good.

Table 31. Comfort Metrics

	Before HP installation	After HP installation
Heating	Winter 2010-11	Winter 2012-13, 2013-14
Avg. indoor space temp. (°F)	69.7	69.3
% hours with average temp <68°F	33%	27%
% hours with temperature spread between floors >4°F	4.5%	12.0%
% hours with average temp >72°F (overheating)	18%	
Cooling	Summer 2011	Summers 2012, 2013, 2014
Avg. indoor space temp. (°F)	76.0	72.0
% hours with average temp >78°F	30.5%	1.4%
% hours with temperature spread between floors >4°F	43.2%	10.1%
Cooling - second floor		
Avg. indoor space temp. (°F)	76.0	69.7
% hours with average temp >78°F	41.0%	8.7%
Relative Humidity	Nov 2010-Dec 2011	May 2012-Sept 2014
% hours over 60% RH	5.3%	3.2%

5.3.5 Electricity Use Trends

Figure 78 shows the variation of the heat pump energy use and power over the monitoring period. The figure displays that cooling demand was consistent during cooling periods while the operation was interrupted frequently during heating periods. Figure 79 confirms that the energy use by the heat pump for cooling and heating was very modest, reaching as high as 15-17 kWh per day during both periods. The figure also confirms that the impact on the total house electric use was small.

Figure 78. Heat Pump Electric Use for R-House

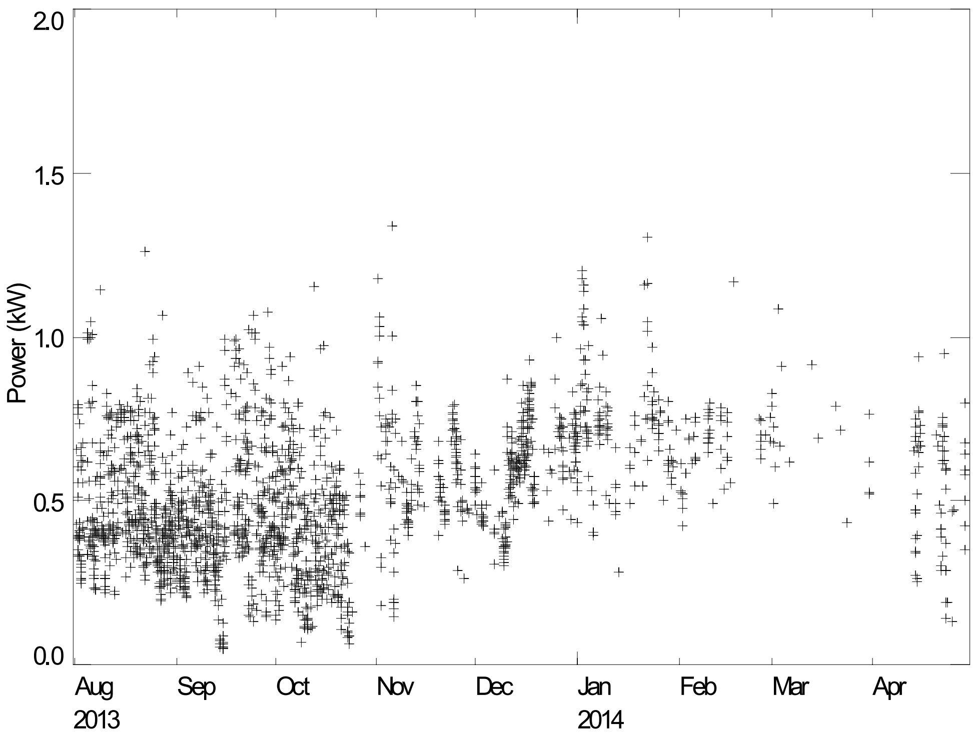
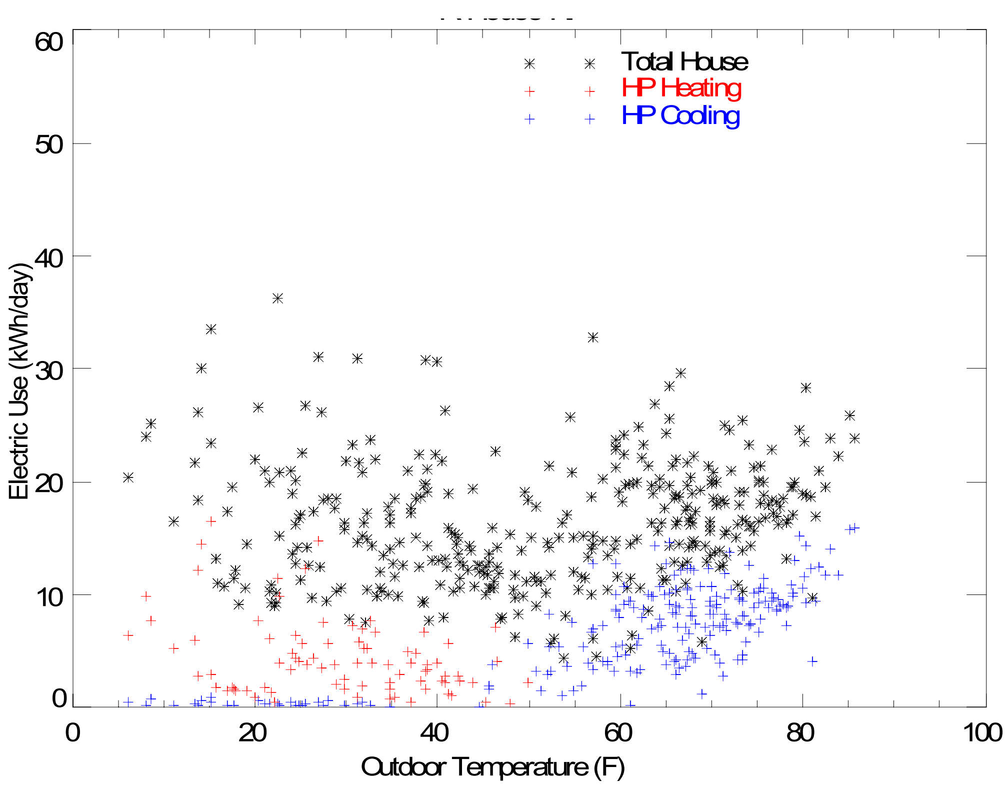


Figure 79. Daily Total and Heat Pump Electric Use vs. Outdoor Temperature for R-House



5.3.6 Total Energy Use Comparison

Monitored energy consumption compared to that predicted by PHPP is shown in Table 32. The monitored period is May and June 2012, and July 2013-April 2014. May and June 2012 were used in place of May and June 2013 because the stuck valve on the heating system distorted ERV heating energy measurements for those two months. The monitored data is shown as weather normalized to the 30-year average heating and cooling degree days for comparison to the model and as actual energy used.

Compared to PHPP, total weather normalized energy consumption was about double. Space heating was higher by 178%; DHW was about 22% higher; and "other" energy was about 50% higher. Predicted cooling energy was negligible, but actual cooling energy was about 1,000 kWh.

Table 32. Comparison of Energy Use to Model – All Converted to kWh

kWh	Monitored	Weather Normalized Usage	PHPP	Variation from model
Total energy	13,472	12,463	6,850	182%
HP energy	1,733	1,415	238	595%
Heating	385	373	170	219%
Cooling	1,348	1,042	68	1532%
Boiler energy	7,789	7,098	3,986	178%
Boiler space heat	4,608	3,917	1,375	285%
Boiler DHW	3,181	3,181	2,611	122%
Other energy	3,950	3,950	2,624	151%

5.3.7 HP Indoor Unit Fan Operation

Figure 80 shows operation modes of the indoor unit fan. It has three speeds (low, med, high) plus a boost mode (Pwr). The lines represent the measurements observed on April 24, 2013. Each speed appears to have a bi-modal trend: one for dry coil (higher amps) and one for wet coil (lower amps). As the unit ran into July, the coil presumably became wetter, so fan amps decreased. The fan current also changes slightly with compressor amps (Figure 81), implying that the airflow changes slightly.

Figure 80. Heat Pump Indoor Unit Working Modes for R-House

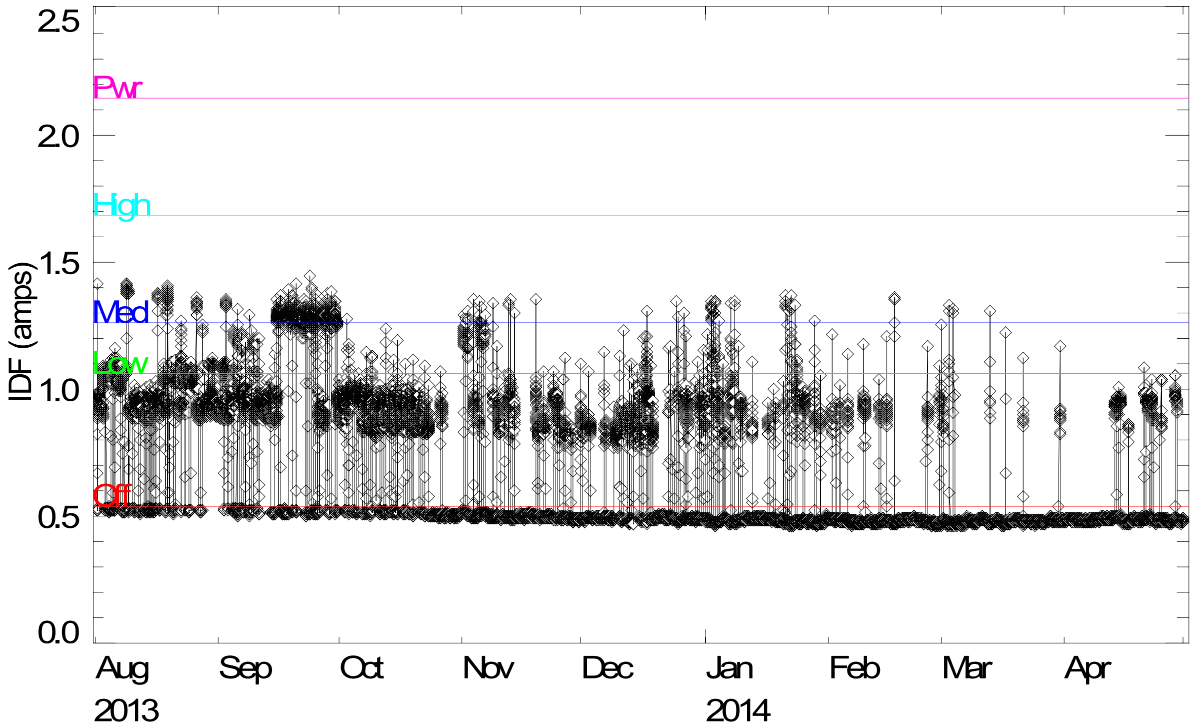
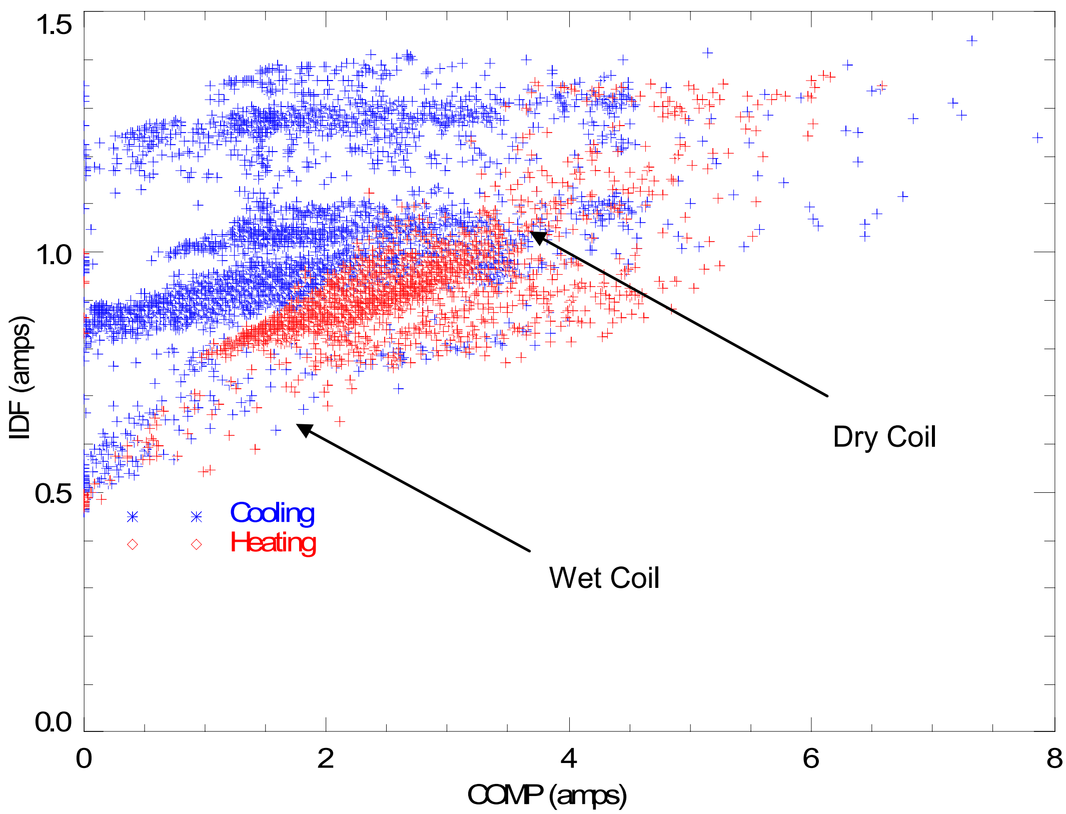


Figure 81. Indoor Unit Fan Current vs. Compressor Current for R-House



5.4 Homeowner Interview

The R-House homeowner was quite satisfied with the overall performance and comfort of the home compared to the two previous homes that she had owned, however numerous problems were mentioned in the interview. The heating and cooling system were only rated as “acceptable.” The heating system was not able to get the home as warm as desired; it was unclear to the homeowner if the thermostat controlling the hot water heating coil was effective. Even after being in the house for over three years she felt unsure about operating the HRV. Satisfaction was high with respect to domestic hot water, quiet environment, lack of drafts, and low utility bills.

5.5 Conclusions for R-House

Lessons from the R-House include the following points:

- The water heater was rated to perform at 80% efficiency at steady state, but measured results indicate that it achieved 70% efficiency over the range of loading conditions.
- Some overheating did exist during heating season, in part due to the heating coil thermosyphon.
- Cooling was required, even though the PHPP model predicted little need for it. Before cooling was installed the house regularly reached 80 °F or higher. Cooling energy was higher than necessary in part because of the thermosyphon at the hot water coil when the ball valve was neglected to be shut.
- Actual energy used was significantly greater than predicted by PHPP.

6 Overall Conclusions

Looking over all three projects, the following observations were made:

- With regard to heat pump location and operation, the differences between the Stuyvesant House and Hudson Passive Townhouses are instructive. The on-off heat pump operation at the Hudson homes caused difficulty in maintaining set points, while the constant heat pump operation at Stuyvesant House achieved set points much more successfully. The Hudson Passive Townhomes finding is consistent with results reported by Ueno (Ueno, Kytrykowska and Bergey 2013), indicating that on-off operation (or deep temperature setbacks) of simplified distribution systems can exacerbate temperature unevenness. The high placement of the Stuyvesant House heat pump also contributed to more successful operation during cooling season compared to Hudson Passive Townhomes's first floor location.
- Solar gain contributed to periods of overheating in two of the projects; whereas trees provided sufficient shading at Stuyvesant House to prevent this problem.
- In three of the four homes, windows were used sparingly for ventilation, even during favorable weather. This result indicates the need to ensure adequate mechanical ventilation and cooling capacity in these tight houses.
- All three Passive House projects used considerably less energy than similarly sized homes built to the New York State Energy Conservation Code. However, energy consumption was 24% to 82% higher than predicted by the PHPP models (Table 33). Plug, lighting, and appliance consumption ("other") was consistently high, but other components varied significantly among the houses due to operational differences. "Other" energy as predicted by PHPP is much lower than these American households. It is presumably based on European assumptions.
- Heating, cooling, and water heating energy use per square foot, normalized for weather, were similar in the Stuyvesant House and Hudson homes. Comparatively, they were much higher in the R-House (Table 34).
- Given the climate, the houses used more energy than expected for cooling. They utilized continuously operating H/ERVs, as well as relatively low capacity heat pumps (with long recovery times). Both encourage keeping windows closed, and as observed in these homes, advise operating the heat pumps continuously. Thus, occupants left the windows closed even when free cooling was available. The highly insulated and airtight enclosures (with high solar gain windows) retained the day's heat far into the night, requiring higher cooling energy use. Taking advantage of free cooling in these Passive Houses in this climate (with significant diurnal temperature swings) requires more operational foresight. When to open/close windows and when to turn on/off equipment becomes a complicated decision, so it is simpler and advisable to leave windows closed and the systems on.

Table 33. Variation in Weather Normalized Site Energy Consumption from PHPP Models

	Stuyvesant	Townhome A	Townhome B	R-House
Total energy	157%	124%	173%	182%
Heating	186%	26%	60%	278%
Cooling	367%	98%	97%	1532%
DHW energy	59%	123%	166%	122%
Other energy	239%	288%	573%	151%

Table 34. Weather Normalized Site Energy Consumption (kWh) for Selected End Uses per HDD, CDD or occupant

In this comparison the R-House heating and DHW energy appears higher than the other houses in part because this table displays site energy; if source energy were shown the figures for Hudson homes and the Stuyvesant House would be roughly tripled.

	Stuyvesant	Townhomes combined	R-House	Units
Heating	0.10	0.09	0.51	Watts per HDD-sf floor area per year
Cooling	0.53	0.34	1.11	Watts per CDD-sf floor area per year
DHW energy	696	956	2,121	kWh per occupant per year

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Final Report
November 2014

Report Number 14-44

State of New York
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