Integrated Controls for Ductless Mini-Splits and Legacy Central Heating Systems

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NEW YORK STATE | NYSERDA

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NYSERDA Record of Revision

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Revision Date	Description of Changes	Revision on Page(s)
Add Date	Original Issue	Original Issue
9/21/2023	Change the weather-normalized total heating energy-use savings experienced during the integrated control condition ranged from “30.3% to 31.6%” to “-30.3% to 31.6%”	iv
9/21/2023	Change the predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from “3.3% to 30.2%” to “3.3% to 29.7%”	iv
9/21/2023	Change the weather-normalized total heating energy-use savings experienced during the integrated control condition ranged from “30.3% to 31.6%” to “-30.3% to 31.6%”	ES-2
9/21/2023	Change the predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from “3.3% to 30.2%” to “3.3% to 29.7%”	ES-2
9/21/2023	Change on a total heating energy basis, heating energy savings ranges from “30.3% to 31.6%” to “-30.3% to 31.6%” per site	15
9/21/2023	Change the fossil fuel heating savings generated by the integrated controller ranges from “30.4% to 35.4%” to “-30.4% to 35.4%”	20
9/21/2023	Change the predicted heating electricity use generally increased during the integrated control condition, with savings ranging from “30.2% to 26.8%” to “-29.7% to 26.8%”	20
9/21/2023	Change the predicted electricity heating was 11,749 kBtu for the baseline (the same model as the total since there was no gas use) and 11,526 kBtu for the integrated control condition for slight savings of “21.9%” to “1.9%”	32
9/21/2023	Change total, weather-normalized, heating energy use savings experienced during the integrated control condition ranged from “30.3% to 31.6%” to “-30.3% to 31.6%”	37
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9/21/2023	Change the predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from “3.3% to 45.9%” to “3.3% to 29.7%	38

Integrated Controls for Ductless Mini-Splits and Legacy Central Heating Systems

Final Report

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Abstract

Integrated Controls for Ductless Mini-Splits and Legacy Central Heating Systems was a field test project that sought to demonstrate how integrated controls can maximize the effectiveness of air source heat pumps in existing homes. The project team identified and recruited 12 sites to install integrated controls that allowed ductless mini-splits to coordinate operation with legacy fossil fuel systems in homes in the New York Metropolitan Area. The integrated controls were installed and monitoring equipment added from 2019 through early 2022. The legacy heating systems of seven sites are hydronic boilers and those of the remaining five sites are forced-air systems with furnaces. From one to three heat pump systems were installed with up to seven indoor heads. Two to seven integrated controllers were installed per site. Heat pump electric consumption, space temperature and relative humidity were measured at each site for at least one heating season. Legacy system fuel consumption was inferred from measured system runtime. "Flip-flop" tests (where the home temporarily switched off integrated control function) were conducted to evaluate effectiveness of the integrated control on both energy use and occupant comfort. By applying typical meteorological year weather data to linear regression models created for each site, total heating energy use differences between the baseline (when the integrated control was turned off) and the integrated control conditions were evaluated. Weather-normalized total heating energy-use savings experienced during the integrated control condition ranged from -30.3% to 31.6%. Aside from three sites with essentially no fossil fuel use during the baseline condition, overall, the fossil fuel heating use savings tabulated during the integrated control condition was positive as expected, ranging from 3.4% to 35.4%, except for one site with negative savings of 30.4%. The predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from 3.3% to 29.7%, while the remaining four sites showed savings ranging from 1.9% to 26.8%.

Keywords

Cold-climate air source heat pumps, Integrated Controls, Measurement and verification

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Acronyms and Abbreviations

AC	air conditioning
AHU	air handling unit
ASHP	air source heat pump, also air-to-air heat pump
ccASHP	cold-climate air source heat pump
CT	current transducer
DHW	domestic hot water
FSEC	Florida Solar Energy Center
FFT	flip-flop test
ft.	feet or foot
GHG	greenhouse gas
GPS	global positioning system
head	indoor component of a ductless ccASHP. Also known as section or unit
HOBO	Honest Observer by Onset
hr.	hour
HSPF	heating seasonal performance factor
HVAC	heating, ventilating and air conditioning
IC	integrated control
kW	kilowatt
kWh	kilowatt hours
kBTU	kilo British thermal units
NEEP	Northeast Energy Efficiency Partnerships
NY	New York
NYS	New York State
NYSERDA	New York State Energy Research and Development Authority
PON	Program Opportunity Notice
PV	photovoltaic
RH	relative humidity
sq	square
TMYx	Typical Meteorological Year, sourced from 2006 through 2021
W	watts

Executive Summary

The project was initiated under New York State Energy Research and Development Authority's (NYSERDA) Program Opportunity Notice 3519. The objective of this project was to demonstrate how integrating controls can better manage the operation of each system, generate energy savings, and maintain comfort in all spaces. The project team identified and recruited 12 sites to install integrated controls that allowed cold-climate air source heat pumps (ccASHPs) to coordinate operation with legacy fossil fuel systems (boilers or furnaces) in homes in the New York Metropolitan Area . MaGrann Associates coordinated the overall project after acquiring the contract from The Levy Partnership, Inc. in March 2022 (staff were consistent throughout the project). Centsible House was primarily responsible for site recruitment and coordinating controller installation. MaGrann Associates and Florida Solar Energy Center (FSEC) conducted measurement and verification of the sites. Pacific Northwest National Laboratory (PNNL) conducted product research and performed energy modeling. Northeast Energy Efficiency Partnerships (NEEP) coordinated the advisory panel and some dissemination activities.

The integrated controls were installed and monitoring equipment added between 2019 and early 2022. The legacy heating systems of seven sites are hydronic boilers and those of the remaining five sites are forced-air systems with furnaces. The ccASHPs were mostly ductless units with multiple indoor heads. From one to three heat pump systems were installed with up to seven indoor heads. Two to seven smart controllers were installed per site to integrate the ccASHPs and the legacy system.

The monitoring and analysis approach measured electric consumption at one-minute intervals for all the installed heat pumps for at least one heating season. Fuel consumption data of legacy heating systems were inferred from the measured system runtime at the same interval. Loggers were installed to measure space temperatures and relative humidity (RH) at 15-minute time intervals in some rooms in each house. Hourly outdoor temperature and relative humidity was collected from the National Weather Service from three New York State weather locations near the study sites. “Flip-flop” tests (where the home temporarily switches off integrated control function) were conducted to evaluate effectiveness of the advanced control schemes. Linear regression analysis was conducted with data from each site to weather-normalize the monitored heating energy use, so that changes in heating energy use attributing to the integrated controller could be quantified. Models that predict daily average heating energy use as a function of daily average outdoor temperature were constructed for each site. By applying typical meteorological year weather data, total heating energy-use differences between the baseline (when the integrated control was turned off) and the integrated control conditions were evaluated for each site. Considering the primary objective of the project was to evaluate the ability of the integrated controller to reduce fossil fuel use, irrespective of total energy savings, heating-energy use was analyzed separately for fossil fuel and electricity.

Total, weather-normalized, heating-energy use savings experienced during the integrated control condition ranged from -30.3% to 31.6%. Aside from three sites with essentially no fossil fuel system use during the baseline condition, overall, the fossil fuel heating use savings tabulated during the integrated control condition was positive as expected, ranging from 3.4% to 35.4%, except for one site with negative savings of 30.4%. The predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from 3.3% to 29.7%, while the remaining four sites showed savings ranging from 1.9% to 26.8%.

Homeowner surveys indicated that most were satisfied with the heat pump system and thought the installation process was no more onerous than a normal replacement of their original heating and cooling systems. A few homeowners, however, complained about the operation of the integrated controllers and communication between the ccASHP and the legacy system. The main homeowner motivations for installing the heat pumps were to lower operating costs and improve comfort.

While most homeowners were satisfied with the heating performance of the ccASHP systems, respondents from three homes complained about the legacy system, reporting it turned on less frequently than expected. Although less use of the legacy system was intended, there were at least two incidents where defective controllers failed to enable the legacy system when needed. Combining the feedback from the residents and the data analysis results, none of the control schemes used in this project fully met expectations. Controller manufacturers must address both software and hardware issues, so that the product works as intended. Integrated control of two independent systems is relatively new to customers. Therefore, to be successful, a higher level of customer service covering guidance on initial setup and answering ongoing questions during regular use is needed. More intuitive interfaces are highly encouraged.

1 Project Introduction and Overview

1.1 Background

There is a trend for homeowners to install efficient ductless air source heat pumps (ASHP) to supplement less efficient existing space conditioning systems, with homeowners adding one unit in a central living area (Cadmus 2016). Because of the potential for ASHPs to save energy by providing a large portion—up to 77% (Metzger et al. 2018) of the space conditioning—utilities have incentivized this strategy. However, post-installation evaluations suggest ASHPs are not reaching full potential because existing central heating systems continue to operate more than necessary in these combined systems. This project investigated the potential to maximize savings from supplemental ASHPs by using integrated controls to manage the interaction of multiple space conditioning systems.

This opportunity is significant for New York State because of its many homes with inefficient central heating systems, many of which provide inadequate comfort due to antiquated equipment and/or sub-standard distribution. According to the 2015 Residential Energy Consumption Survey, about 51% of homes in the northeast census region (which includes NYS) have central warm air furnace heating, most of which use natural gas. Approximately half of the remaining 49% are steam/hot water systems which burn fossil fuels, and some are inefficient electric systems (electric resistance or low-HSPF heat pumps). NYS and New York City (NYC) want to increase efficient electrification of space conditioning so it can be paired with on-site photovoltaics (PV) and a future cleaner electric grid to reduce carbon emissions, as compared with burning fossil fuels on site in furnaces and boilers (NYC Mayor's Office of Sustainability 2016).

1.2 Objective

The objective of this project was to demonstrate how integrating controls can better manage the operation of each system, generate energy savings, and maintain comfort in all spaces. An integrated control system should maximize the share of heating load fulfilled by the efficient heat pump and minimize the share fulfilled by the legacy central system. It should improve overall HVAC efficiency by eliminating the "take-back" penalty of between 25%–75% of energy savings found by some researchers where ccASHPs have been installed in homes with existing fossil fuel systems (Cadmus 2016). These systems would be better able to use "smart" or "learning" capabilities present in many of today's thermostats, and better integrate with smart grid and demand response platforms.

Three strategies were researched:

1. For existing central forced air furnaces/AC: control central system based on ASHP settings.
2. Also, for existing central forced air furnaces/AC: manufacturer-specific controls to control both systems as one.
3. For central hydronic with zonal radiators: connect ASHP and zonal radiators to external controls.

1.3 Scope

By the end of the project, 12 demonstration retrofits were each completed with one of two control strategies. The project scope included the following:

1. Convening representatives from manufacturers, utilities, and efficiency programs in an advisory panel to guide the project and manage risk by assisting to overcome challenges. A manufacturer sub-committee contributed control hardware.
2. Developing a measurement and verification (M&V) plan for each of the control strategies that included M&V equipment, installation details, and data collection and analysis methodology.
3. Recruiting participants and installing equipment at 12 demonstration retrofit sites. One of the integrated controls systems was deployed at each site.
4. Modeling three options for controlling ductless heat pump systems in existing homes with other equipment and calibrating these models to data obtained from field tests, with EnergyPlus as the primary modeling tool. The model was then extrapolated to three New York State climate locations (one in each International Energy Conservation Code climate zone). See attachment for report on this modeling exercise.
5. Collecting and analyzing data on central and ASHP system energy use, runtime, and indoor environmental conditions for up to 12 months, with and without the integrated control system operating in alternating time periods of two to four weeks each. Collecting occupant feedback on the control strategies and analyzing data to determine the effectiveness of each strategy and potential for improvement. Control strategies were refined during the demonstrations in response to occupant feedback.
6. Developing and implementing a dissemination plan that promulgated project results to heat pump and controls manufacturers, utility program managers, and design/HVAC professionals.
7. Preparing this final report, covering all aspects of the work.

2 Methodology

2.1 Site Recruitment and Installation

Twelve demonstration sites were recruited. Most sites were single-family homes, either attached or detached, and one was an apartment in a small multifamily building.

Site recruitment screening characteristics included the following:

1. Be a New York State residential dwelling.
2. Have a dedicated heating system that only serves that dwelling.
3. Have a heating system that is centrally controlled and in good working order.
4. Have as the home's primary heat fuel source electric (resistance or non-high-performance heat pump), natural gas, liquid propane gas, or fuel oil.
5. Pay into the System Benefits Charge on electric utility bill.
6. Be fully occupied year-round.
7. Have a home layout suitable for the objective of providing a substantial portion of heat via a limited number of centrally located ASHP air handlers.
8. May have a ASHP already installed, in addition to older central heating system, or may require a newly installed ASHP.

The recruitment team found it difficult to identify suitable sites where only one or two heat pump air handlers were installed or desired; however, many more sites were found where larger heat pump systems were being installed, overlaying existing central fossil fuel systems. Therefore, the parameters of acceptable dwellings were widened to include this more prevalent installation type.

2.2 Control Product and Strategy

Different control strategies were proposed and researched during the preliminary phase of the project. All except two strategies were dropped due to the lack of market-ready products and the expected difficulties of implementation. The selected control strategies are as follows:

The first control strategy is a mix of wired and wireless solutions for central forced air systems. This solution uses a set of products that are available on the market today which create a two-stage approach to heating, with a ductless ASHP used as the first stage and the central forced air system as the backup, while providing flexibility for scheduling and other smart features. This solution requires one Wi-Fi controller to communicate with each heat pump air handler, a central thermostat wired to the legacy system, a software interface for the user, and optional remote sensors. Below are descriptions of these components for this strategy and the names of the products used in the demonstration sites.

Ductless ASHP Wi-Fi Enabled Controller: To interface with the ASHP, the wireless controller communicates with the ASHP through a radio frequency signal. The wireless controller mostly works as a remote control for the ASHP with basic functionalities, while allowing smart features such as scheduling. Ductless ASHP Wi-Fi enabled controllers used in the project were Resideo D6, Flair Puck Pro, and Daikin DKN Wi-Fi adapter.

Figure 1. Wi-Fi Controllers by Honeywell Home (Resideo) and Flair

Connected Central Thermostat: To communicate with the central system, a smart thermostat replaces the legacy thermostat. The smart thermostat is an internet-connected thermostat that can send and receive signals from a central air handler, furnace, or boiler. Unlike the ductless ASHP Wi-Fi enabled controllers, the smart thermostat is hard wired to the legacy system. It can run multistage heating and cooling systems, as well as air circulation during different times of the day. The smart thermostat can be purchased with occupancy sensors that can be integrated into the control strategy. For example, if the ASHP in the main zone is able to satisfy the main zone temperature, but a smart sensor located in a remlote bedroom reports that the remote room is not achieving desired comfort, central system fan cycling could be initiated to attempt to increase bedroom temperature via mixing. If desired temperature is not achieved within a pre-determined interval, heating via the central system can be initiated. Smart central thermostats used in the project include Resideo T10, Google Nest, Ecobee 4, and Honeywell smart thermostat.

Figure 2. Connected Central Thermostats by Honeywell Home (Resideo) and Ecobee

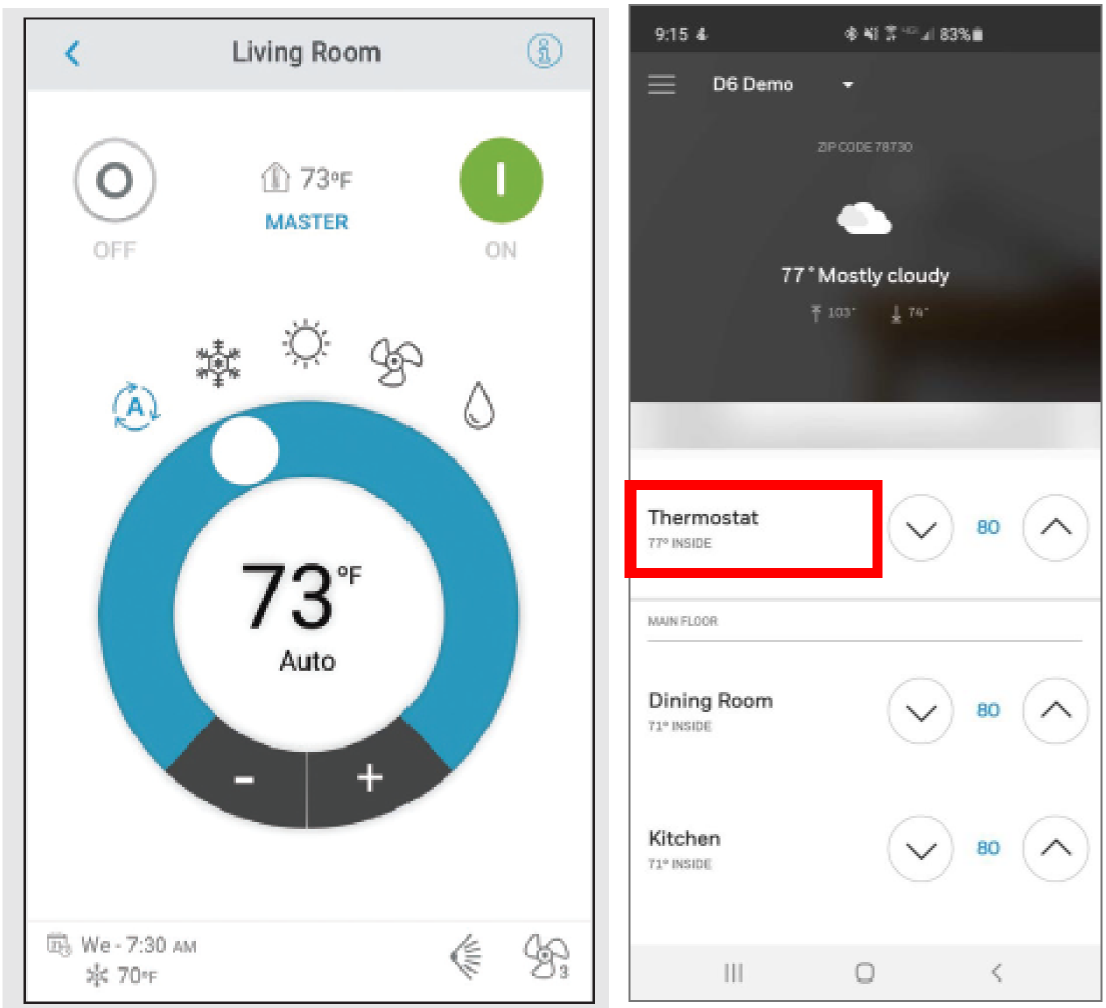
Smart Sensor: This optional feature enables occupancy sensing and allows the control strategy to factor in rooms without heat pump indoor heads when calculating average room temperature. It is a wireless sensor connected directly to the Wi-Fi system in the home and located in a bedroom to measure room temperature and optionally, occupancy activity. The demonstration sites using Resideo control products usually installed one to four smart sensors along with the central thermostat.

Note that both the central thermostat and the Wi-Fi controller mentioned above are also capable of occupancy sensing. Residents are provided with options to enable or disable motion detection.

Interface to Connect All Components: Each of the control products mentioned above provides its own mobile application which provides a control interface for the resident and provided the project team access to the application program interface (API) for the corresponding control system components. The application can configure and control most of the features in the control products. Graphic user interface examples of Resideo and Flair Puck Pro are shown in the figure below.

Figure 3. Screen Captures of Graphic User Interfaces

Flair Puck (left) and Resideo (right)



The General Integrated Control Scenario: a typical integrated control heating scenario of the Resideo system is as follows:

- Set up a compatible mini-split heat pump as the primary heat (first stage) with central system as backup heat (second stage).
- Mini-splits are controlled by the Wi-Fi controller to provide heat in accordance with the control algorithm.
- Central System turns on and begins heating when either the:
    - Outdoor temperature falls below a set threshold, typically at a relatively low temperature such as 5 degrees F.

    - Indoor temperature at the central thermostat falls more than a preset number of degrees (known as the "droop") below the setpoint. Droop is typically set at 5 to 10 degrees F temperature differential.

- After the central system activates, the thermostat follows its programmed schedule normally and the ASHP is set to "off" mode.
- As a safety mechanism, when ASHP is active, the thermostat remains in the heating mode and is set to 60 degrees F as a fail-safe in case the central system fails.
- Cooling is not integrated and will operate normally. Space cooling systems integration may be a future product enhancement.

Other features available with the integrated controllers are scheduling and geofencing. Scheduling of night and daytime setpoints was used by most sites. Only Site 5 was known to use the geofencing function. Geofence is a feature of Resideo App that can trigger controller activity depending on whether the resident is home or away using the GPS on their smart device. When the user crosses the geofence boundary, the Resideo App updates controllers in accordance with the preferred "home" or "away" settings.

The second control scenario is a mix of wired and wireless solution for central hydronic systems. This solution implements the same control strategy and the same set of products that are used in the solution above, but applied to central hydronic systems. This solution also utilizes the same control products.

Other solutions proposed and researched at the early stage of the project included: wired solution for central forced air system, wired solution for hydronic system, solution for central hydronic system with zone controller, and solutions that require integration between control products and third-party smart thermostat through API connection. The two wired solutions are similar to the mixed control solutions, but use all wired products. The zonal control solution uses Wi-Fi enabled controller that screws onto existing radiators and can open and close the hot water valves as controlled by an app. Multiple radiators can all be controlled on the same interface. The advantage of API connection solutions is that it is highly flexible and programmable. But this approach requires programming expertise of and compatibility of both the control product and the thermostat. After market research, team discussions, and consulting manufacturers on the Advisory Panel, these solutions were dropped considering the lack of suitable or effective control product on the market and difficulties of actual implementation.

Slight variations of the control components combinations described above were required depending on the demonstration homes' existing HVAC system, home size, and layout. For example, homes with two stories often required a slightly different control configuration than single-level homes. Other site-specific challenges were observed and addressed on site. See Lessons Learned of this report for details regarding these challenges.

2.3 Data Collection and Analysis

The project team collected detailed data on central and ASHP system energy use, runtime, and indoor environmental conditions for a full-heating season for most sites, with and without the integrated control system operating over alternating periods. Some sites had to be cut short because of the pandemic and the project deadline. Outdoor environmental conditions of demonstration homes were collected from a nearby weather station. The project team also conducted interviews or surveys to collect occupant feedback on the control strategies and any changes to the occupancy or space use. The project team analyzed the data on changes in energy use because of the retrofits and, separately, as a result of each control strategy to determine the effectiveness of each strategy and potential for improvement over the baseline uncontrolled approach. Control settings were sometimes adjusted during the demonstrations in response to occupant feedback. See section 3.2 for details of instrumentation and data collection.

2.4 Instrumentation

Energy use and interior temperatures were monitored at the study homes as summarized in Table 1. Energy data were collected on a one-minute time step as well as a temperature and relative humidity data on a 15-minute time step. Temperature and relative humidity data were monitored real-time with the Point Six monitoring device, and recorded with a more accurate HOBO device, with data manually retrieved from the sites during periodic visits.

Table 1. Monitoring Equipment and Accuracy

Measurement	Equipment	Accuracy
ASHP and fossil fuel equipment electric energy	SiteSage Energy Monitor with Current Transformers	±1% of rated current
Fuel fired furnace / boiler runtime: AC current of fuel valve	SiteSage Sensor Pod with Acuamp ACTR Series AC current transducer	±1% of full scale
Indoor temperature and relative humidity: real time monitoring	Point Six 3008-04-V6 Wi-Fi transmitter	±0.4°C, ±3% RH
Indoor temperature and relative humidity: analysis purposes	Onset HOBO UX100-011A	±0.21°C, ±2.5% RH

Hourly outdoor temperature and relative humidity was collected from the National Weather Service from three New York weather locations near the study sites: LaGuardia Airport, John F. Kennedy Airport, and Westchester County Airport. The stated accuracy of the outdoor temperature measurements by the National Weather Service is ±1°F. Indoor temperatures were measured using Onset HOBO UX100-011A portable loggers with a stated accuracy of ±0.21°C for temperature and ±2.5% RH for relative humidity up to 90%, and using the Point Six wireless transmitter with the Sensirion SHT71, with stated accuracy of ± 0.4°C, at 25°C and ±3% RH (from 20-80%).

Each site had four to six HOBO temperature and RH sensors deployed, one in each bedroom and in all main living areas excluding the kitchen. Point Six temperature and humidity loggers were also deployed in select bedrooms and main living area of the homes. Temperature and humidity monitors were placed on interior walls, away from direct sunlight, about head-height, and away from mechanical system supplies and other heat-generating devices. Guidelines provided in the Building America Indoor Temperature and Humidity Measurement Protocol (Metzger and Norton, 2014) were followed.

Electric energy use of heat pumps and fossil fuel systems was measured by SiteSage loggers, with included current transformers. These have a stated accuracy of ±1% between 10% and 130% of their rated output. Rather than measure natural gas and fuel oil flow directly, fossil fuel energy use of central forced air furnace and hydronic system was determined via monitoring of the fuel valve at the space conditioning appliance using a low current, Acuamp current transformer. The Acuamp CT monitored actuation of the fuel valve, giving an indication of appliance On/Off status. Fuel flow during active space conditioning was recorded at the fuel meter to determine the rate of consumption and used to convert the monitored value into fuel flow. While not as accurate as a direct measurement of fuel flow, it is expected that for a single stage, non-modulating burner, the method is sufficiently accurate when comparing energy use in a pre/post situation. While fluctuations in line pressure as a result of delivery pressure, or simultaneous fuel flow to other appliances, can add error to the estimation, individual appliances typically have fuel regulators that act to deliver a relatively constant fuel flow according to appliance needs. Henderson et al. (2013) shows a strong correlation between estimating oil use based on burner runtime and direct measurements, implying the runtime method of determining fuel oil use to be useful with reasonable accuracy.

3 Results

3.1 Home Characteristics and Equipment Details

Table 2 contains information on each demonstration site. Sites ranged in size from 913 square feet (sq. ft.) to 5,093 sq. ft. Eight of the homes were single-family homes and four were dwellings in multiunit buildings. Half of the sites had oil- and half had gas-fired space heating systems.

Table 2. House Characteristics

Site	City or NYC Borough	Heated Area (sq ft)	House Type	Space Heating Fuel
1	Queens	1,152	SFA	Gas
2	Bronx	1,189	SFD	Oil
3	Queens	913	MF unit	Oil
4	Bronx	1,101	SFD	Gas
5	Brooklyn	5,093	MF unit	Oil
6	Ossining	2,069	SFD	Oil
7	Brooklyn	1,200	MF unit	Oil
8	Brooklyn	2,100	MF unit	Oil
9	Bronx	1,240	SFD	Gas
10	New Rochelle	2,567	SFD	Gas
11	Montrose	1,025	SFD	Gas
12	White Plains	1,800	SFD	Oil

Table 3 summarizes the legacy system type, number of heat pumps installed and advanced control strategies of the twelve sites. Half of the sites had oil-fired hydronic system and half gas-fired forced air system.

Table 3. Installed Site System Configurations

Site:	Legacy Space Heating System	Legacy Space Heating System Observed/Rated Fuel Input Rate (btu/hr)	Number of Heat Pumps (outdoor/indoor)	Advanced Control Details
1	Fuel fired furnace	133,773	2/2	Resideo T10 & D6; 15 °F outdoor changeover; 5 °F droop
2	Fuel fired hydronic boiler	116,144	1/1	Resideo T10 & D6; 15 °F outdoor changeover; 5 °F droop
3	Fuel fired hydronic boiler	103,700	1/2	Resideo T10 & D6; 15 °F outdoor changeover; 5 °F droop
4	Fuel fired furnace	143,106	1/1	Resideo T10 & D6; 15 °F outdoor changeover; 5 °F droop
5	Fuel fired hydronic boiler	143,106	1/1	Resideo T10 & D6; 15 °F outdoor changeover; 5 °F droop
6	Fuel fired hydronic boiler	207,750	3/7	Daikin's DKN Plus & DKN Wi-Fi adaptor; 23F outdoor changeover; 4F droop; indoor heads with individual setpoints, droop control is based on one single indoor head
7	Fuel fired hydronic boiler	52,000	1/3	Resideo T10 & D6, Tenants are not using schedules; 15F outdoor changeover; 5F droop
8	Fuel fired hydronic boiler	164,000	1/5	Daikin's DKN Plus & DKN Wi-Fi adaptor; 23F outdoor changeover; 4F droop; indoor heads with individual setpoints, droop control is based on one single indoor head
9	Fuel fired furnace	103,875	2/4	Resideo T10 & D6
10	Fuel fired furnace	140,000	2/5	Daikin's DKN Plus & DKN Wi-Fi adaptor; 23F outdoor changeover; 4F droop; indoor heads with individual setpoints, droop control is based on one single indoor head
11	Fuel fired furnace	90,025	1/5	Flair Puck Pro, 23F outdoor changeover; no droop control
12	Fuel fired hydronic boiler	150,000	2/7	Daikin's DKN Plus & DKN Wi-Fi adaptor; 23F outdoor changeover; 4F droop; indoor heads with individual setpoints, droop control is based on one single indoor head

Table 4 summarizes the number of control products, the type of control products and the corresponding cost. Demonstration sites used at least two and at most seven Wi-Fi controllers. Control products cost from $100 to $295 for each unit. Control product costs for each site ranged from $343 to $1,855, not including installation labor.

Table 4. Installed Control Equipment Cost

	Central T-stat			Wi-Fi Controller			
Site	Model	Unit Price	Qty.	Model	Unit Price	Qty.	Total Cost
1	T10	$243	1	D6	$100	2	$443
2	T10	$243	1	D6	$100	1	$343
3	T10	$243	1	D6	$100	2	$443
4	T10	$243	1	D6	$100	1	$343
5	T10	$243	1	D6	$100	1	$343
6	DKN Plus	$295	1	DKN Wi-Fi	$260	6	$1,855
7	T10	$243	1	D6	$100	3	$543
8	DKN Plus	$295	1	DKN Wi-Fi	$260	4	$1,335
9	T10	$243	1	D6	$100	3	$543
10	DKN Plus	$295	1	DKN Wi-Fi	$260	4	$1,335
11	Flair Puck Pro	$129	4	Honeywell	N/A (existing)	1	$516
12	DKN Plus	$295	1	DKN Wi-Fi	$260	6	$1,855

3.2 Analysis

3.2.1 Data Analysis

The fossil fuel (legacy) system and heat pump were both used to provide heating at each site. Each site was monitored under two conditions: one without a controller linking operation between the two systems (baseline) and one with a controller coordinating operation of the heating systems (integrated control). For the sites set up and instrumented early in the study, we were able to collect data for long periods under both conditions and capture like-days under each condition for evaluation. At some homes, there were multiple transitions between conditions in attempt to get a full range of heating weather during each condition; at other homes there is only one transition. While the project scope called for more frequent transitions, the team decided fewer homeowner interruptions were preferable to minimize homeowner adjustment time for controller changes. For the last seven homes established in the study, one winter (or just a small portion of one winter) was available for both conditions to be tested, which resulted in much smaller data sets and one transition. Table 5 presents the start and end dates for monitoring under each condition.

Table 5. Start and End Dates for Baseline and Integrated Control Experiments

Site Number	Integrated Control Start Date	Baseline Start Date	Integrated Control Start Date	Baseline Start Date	End Date
1		1/29/2020	2/16/2020	2/18/2021	7/31/2021
2		1/29/2020	2/16/2020	2/4/2021	8/1/2021
3	9/17/2020	2/5/2021			3/4/2022
4		1/27/2021	3/19/2021		4/20/2022
5	1/21/2021	3/16/2021	4/1/2021	2/2/2022	4/20/2022
6*	12/28/2021	2/2/2022	3/22/2022		4/20/2022
7	10/22/2021	2/2/2022			4/20/2022
8	11/15/2021	2/5/2022			4/20/2022
9	11/8/2021	2/2/2022			4/20/2022
10	1/19/2022	2/22/2022			4/20/2022
11	3/14/2022	3/30/2022			4/20/2022
12	12/2/2021	2/8/2022			4/20/2022

* Monitoring issues at Site 6 prevented an evaluation of this site.

Linear regression analysis was conducted with data from each site to weather-normalize the monitored heating energy use, so changes in heating energy use attributed to the integrated controller could be quantified. Similar past studies that have established the most robust statistical formulation to predict heating and cooling depending on weather (Sutherland, 2016) use the same method independently identified by Haberl et al. (2005). This is currently recommended in the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE) "tool kit"—recommendations for methods to estimate savings from retrofit measures applied to buildings. The following theoretical model based on suggested ASHRAE protocols (ASHRAE 2002) was considered for predicting energy use:

$$\textbf{Energy} = \mathbf{A + B(T_{amb} - T_{int})}$$

Where:

A = regression error or intercept term

B = coefficient for house heat gain (UA)/coefficient of performance (COP) of cooling system (outdoor temperature – indoor temperature; Delta T)

T_{amb} = Outdoor Temperature

T_{int} = Indoor Temperature

However, an alternative model with a substitute B term was used that looks at outdoor temperature rather than outdoor-indoor temperature difference. This was the simplest model that shows stable and reliable results with strong explanatory power. Past studies show that typically outdoor temperature yields better results than outdoor temperature minus indoor temperature, in degrees Fahrenheit (°F, Delta T) unless the interior temperature profile was altered between the pre- and post-retrofit observation periods. However, past evaluations involving ductless heat pumps working in tandem with legacy central space conditioning systems have not used Delta T because of expected behavioral changes. Differences in interior temperature are likely with the ASHP, because uniform interior room temperatures do not typically yield the greatest comfort. Brand (1987) found that space conditioning systems that facilitate zoning have significantly lower energy use. When supplemental ASHP systems are added, it becomes easy—and even likely—that occupants maintain different heating and cooling conditions in different rooms of the home.

The method resulted in a model, for each state, that predicts daily average heating energy use as a function of daily average outdoor temperature. For each site, separate models were constructed for electric heating, fossil fuel heating, and total heating. A daily model is utilized because models with smaller time steps are less statistically robust considering lags in space conditioning system response to outdoor weather as a result various factors including thermal mass.

Because the heat pumps and some legacy systems are also often used for cooling, the upper range of outdoor temperatures that result in a heating operation, or heating balance point, needed to be determined to ensure cooling energy is excluded from the analysis. The balance point was derived via a stepwise fashion by first applying a low-daily average outdoor temperature, and then incrementing the balance point one degree higher until the best model fit was found. Beyond a certain daily average outdoor temperature, the regression strength worsens, as the correlation between weather and heating energy use trend reverses for cooling. This trend from heating to cooling energy is apparent in Figure 4, presented in the next section.

Due to time constraints, data representing an entire heating season, under each test condition, could not be collected at any site. This resulted in homes experiencing different weather during the periods monitored for each condition. To isolate heating energy impacts related to integrated controllers, heating energy use under each condition needs to be compared on the basis of identical weather conditions. Therefore, the models created with monitored data were used to predict heating energy use under each condition by applying Typical Meteorological Year, a collection of selected weather covering the period from 2006 to

2021 (TMYx) weather data for the John F. Kennedy Airport in New York State. While some extrapolation is possible, in general the models are only accurate for the range of weather data associated with the monitored heating energy. Thus, and especially for sites with a short monitoring period, the modeling and analysis was restricted to a common range of daily average temperatures for which heating energy was monitored under each condition, and a full-seasonal comparison is not possible.

3.2.1.1 Total Heating Energy Use Analysis

Using the linear regression models created for each site, and applying the TMYx temperatures as previously described, we evaluated the total heating energy use differences between the baseline and the integrated control conditions. As previously mentioned, this total at each site is for a common range of outdoor temperatures for which data were collected under both conditions. All monitored heating energy was totaled for each condition, including from heating sources not part of the controller integration, such as stand-alone electric space heaters, when existence of such systems was identified during monitoring equipment installation. For some sites, the data revealed that not all heating was captured. Within the site-by-site evaluation, we have indicated if additional heating is either suspected or confirmed by occupants. Monitored electricity use and inferred fossil fuel use were converted to British thermal units for analysis.

Table 6 summarizes the total heating energy use for each condition, and the heating energy savings (or negative savings) for the integrated control condition versus the baseline condition for the annual heating days within the temperature range. On a total heating energy basis, heating energy savings ranges from -30.3% to 31.6% per site. To understand more about this large range, from negative to positive savings, each site, with its individual characteristics needs to be evaluated individually. And given the case-study nature of this evaluation and that potential savings are indicated for a different temperature range at each site, an overall average savings has not been calculated.

Table 6. Total Heating Prediction by Temperature Range Evaluated

Site #	Temperature Range (°F)	Energy Use (kBtu/range)		
		Baseline	Integrated Control	Site Savings
1	26-62	7,149	6,036	15.6%
2	25-68	35,745	35,456	0.8%
3	24-74	50,241	43,297	13.8%
4	35-61	52,174	35,680	31.6%
5	21-61	19,949	17,936	10.1%
6	Not evaluated			
7	24-50	47,251	34,282	27.4%
8	21-55	11,749	12,129	-3.2%
9	22-38	38,535	50,227	-30.3%
10	27-55	19,357	22,888	-18.2%
11	39-57	47,470	32,887	30.7%
12	15-56	19,473	23,035	-18.3%

Table 7 presents model statistics for the total heating energy use analysis including sample size, coefficient of determination (R-squared, R^2), t-statistic, and p-value for the total heating models for the baseline and integrated control conditions, respectively. Note the grey shading for site 7 and site 11, where the R^2, representing the relationship between outdoor temperature and energy use is very poor. For these sites, outdoor temperature explains much less than half ($R^2 < 0.50$) of the heating use and the statistical significance of temperature dependence (p-value) is weak. The small sample sizes available for these analyses likely contribute to the weakness in the relationship between outdoor temperature and energy use. A related explanation may be that the temperature ranges used for these analyses are somewhat limited, and at milder temperatures there is generally more variability in heating energy used by the occupants. Occupant-induced set point changes resulting in differences between baseline and integrated control conditions may also contribute to model weakness. As previously mentioned, developing a model based on the difference between indoor and outdoor temperature introduces additional error. The integrated controller is also causing changes in indoor temperature.

Table 7. Total Heating Range Model Statistics

Site No.	Baseline				Integrated Control			
	Sample Size (Days)	R-squared	t-statistic	p-value	Sample Size	R-squared	t-statistic	p-value
1	92	0.51	-9.77	0.00	224	0.52	-15.57	0.00
2	117	0.82	-22.80	0.00	195	0.74	-23.65	0.00
3	242	0.71	-24.17	0.00	95	0.82	-20.48	0.00
4	18	0.72	-6.67	0.00	90	0.66	-13.18	0.00
5	160	0.62	-12.12	0.00	143	0.68	-17.45	0.00
6	Not Evaluated							
7	12	0.21	-1.62	0.14	12	0.41	-2.62	0.03
8	66	0.44	-7.07	0.00	65	0.48	-7.55	0.00
9	11	0.83	-6.60	0.00	9	0.88	-7.01	0.00
10	49	0.64	-9.11	0.00	23	0.61	-5.30	0.00
11	19	0.13	-1.58	0.13	14	0.14	-1.42	0.10
12	17	0.89	-10.95	0.00	34	0.82	-11.80	0.00

R-squared (R^2): The proportion of the dependent variable's variance that is explained by the independent variables in a regression model. The closer to 1.0, the stronger the model.

t-statistic: The ratio of the difference between the mean of two samples and the variation that exists within them. For sample sizes used here, a t-value of about 2 or more generally coincides with a significant finding. In the above models, a negative t-statistic indicates a negative relationship between outdoor temperature and energy use.

p-value: The probability that the observed results are due to chance. A p-value of < 0.05 is generally considered significant, meaning the deviation in results is not due to chance alone.

The sample size used for analysis is often much smaller than indicated by the monitored date ranges identified in Table 2. The sample was filtered for occupancy/behavioral changes apparently unrelated to the experiment, missing or bad data, and to match temperature ranges during both test conditions. Samples are also limited to observations where the daily average temperature is within the range of temperatures indicating the best model strengths (e.g. removing days of probable cooling).

3.2.1.2 Heating Energy Use Analysis for Separate Fuels

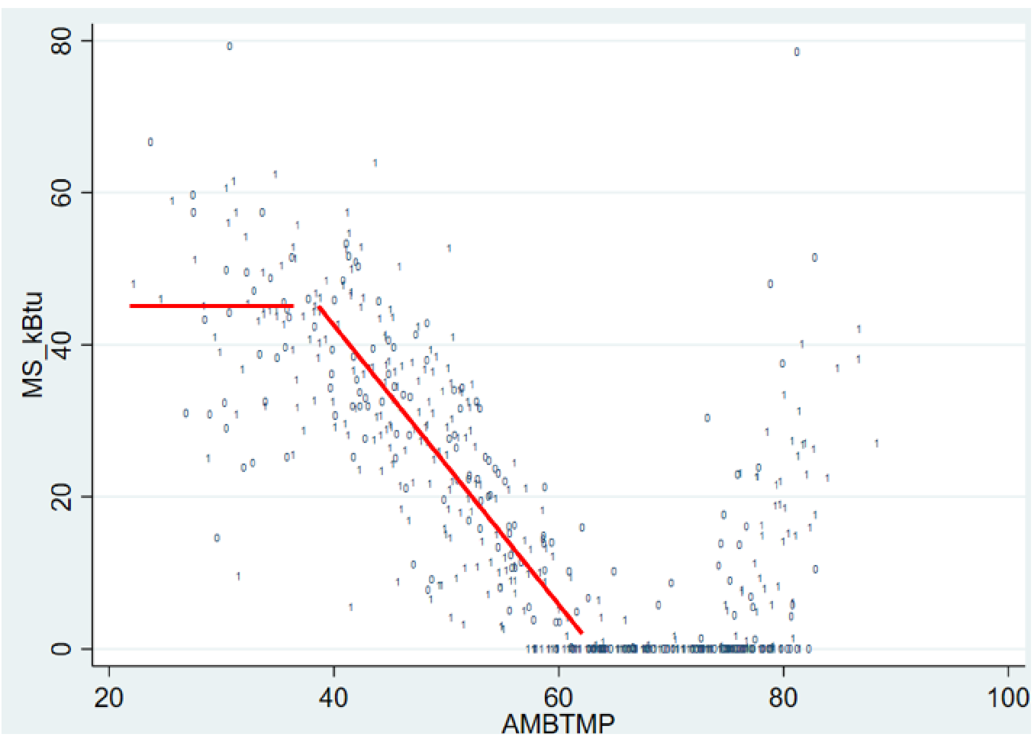
Considering the primary objective of the project was to evaluate the ability of the integrated controller to reduce fossil fuel use, irrespective of total energy savings, heating energy use was analyzed separately for fossil fuel and electricity. The electricity use total includes the ASHP plus electricity use associated with the furnace, as well as uncontrolled electricity (such as a window unit), where monitored.

The same outdoor temperature ranges were applied to the individual fuel use regressions, except that the high-end temperature range of fossil fuel use was limited to the highest average daily temperature of fossil fuel use observed for the baseline and integrated control conditions separately. Generally, this temperature was much lower than that for total heating, as heat pumps were the main source of heat for milder conditions.

One limitation of separate fuel type evaluations is that the sample sizes are often small for fossil fuel use. In a few cases fossil fuel heating was *very* limited or non-existent during one or both test conditions, resulting in very small sample sizes. Another caveat to this breakdown is that the slope of the daily heating electricity use versus daily average outdoor temperature regression for the heat pump is nearly zero at lower daily average outdoor temperatures. Figure 4 provides a good example of the flattening of ASHP use (MS_kBtu on the Y-axis) at lower temperatures (AMBTMP on the X-axis) for site 2. The zeros and ones plotted indicate daily heat pump energy use for baseline and integrated control conditions, respectively. The red lines approximate the regression curves, changing at about 38°F daily average outdoor temperature.

Figure 4. Site 2 Daily ASHP Use Relative to Daily Average Outdoor Temperature

Zeros are baseline and ones are Integrated Control.



Note the large scatter in the ASHP use at the lower temperatures. At the programmed outdoor changeover temperature for the integrated control (15 °F at this site), the heat pump is deactivated. However, on the days when this condition was met, the length of time at this condition varied. In turn, the *daily average* outdoor temperature (which the regressions are built on) for days experiencing short-term outdoor temperatures below 15 °F ranged widely, from about 20 °F to 38 °F. Other days with similar daily average outdoor temperatures may have never experienced short-term outdoor temperatures less than 15°F.

The droop setting of 5°F at this site adds additional variation to how each system performs at a given outdoor temperature. On days that did experience short term temperatures less than 15°F, the timing of the low-temperature period, as well as set point changes, and the impact of the preceding day's weather are all important influences on the dwelling's internal temperature, and influence whether operation of the fossil fuel system is triggered by the integrated control's droop setting.

Considering the complexities of how daily average outdoor temperature affects fuel use, and how it differs with and without use of the integrated control, we developed two independent electricity use regression models for each test period at each site—one for more "mild" temperatures and one for "cold" temperatures. We applied a similar method as used to find the upper bound (balance point) daily average temperature described previously. That is, we modified the middle-range heating regression by stepping up the *lower* bound temperature until we found the strongest regression fit. At sites 5, 7, and 9, this method did not improve the original single electricity use regression for the full range of weather for either test condition. At sites 1, 8, and 12, this technique improved the regression fit for most of the temperature range but left too few data points for a cold weather regression. In these cases, the original single regression was retained for the electricity use prediction. At sites 2, 3, 4 and 10, two regressions for the different temperatures were better than one for one or both test conditions. In those cases, the TMYx average daily outdoor temperature indicated which electricity use prediction model was used for that day's prediction, with one model used for lower temperatures and the other for higher temperatures.

A summary of the fossil fuel and electricity use as well as percentage heating energy savings for the integrated control condition versus the baseline condition is provided in Table 8. The left-hand section pertains to the fossil fuel use prediction, the right side to electricity.

Overall, the predicted fossil fuel use generally decreased during the integrated control condition. There was no fossil fuel use during the baseline condition at site 8 and site 12. There was also very little fossil fuel system use during the integrated control period. Excluding these two sites and site 10 with nearly no baseline use, as well as sites where use has poor relationship to weather, the fossil fuel heating savings generated by the integrated controller ranges from -30.4% to 35.4%.

As expected, the predicted heating electricity use generally increased during the integrated control condition, with savings ranging from -29.7% to 26.8%. The large range in results is unsurprising given the variations at each site in terms of heat pump equipment installed (multiple indoor/outdoor units versus one-to-one units) and controller integration design (differences in outdoor changeover temperature, sensing temperature in multiple rooms, and droop). Nuances of the findings at each site are discussed in the next section.

Table 8. Fossil Fuel and Electricity Heating Prediction by Temperature Range Evaluated

Site No.	FOSSIL FUEL Heating Use Prediction (kBtu/range)			ELECTRICTY Heating Use Prediction (kBtu/range)		
	Baseline	Integrated Control	Savings	Baseline	Integrated Control	Savings
1	2,159	968	55.2%	4,687	4,843	-3.3%
2	29,437	28,438	3.4%	6,739	6,961	-3.3%
3	48,406	40,552	16.2%	3,025	2,819	6.8%
4	46,903	30,315	35.4%	3,448	5,033	-45.9%
5	16,354	14,606	10.7%	4,835	3,538	26.8%
6	Not evaluated					
7	40,677	24,119	40.7%	6,574	5,820	11.5%
8		397		11,749	11,526	1.9%
9	36,701	47,849	-30.4%	1,834	2,378	-29.7%
10	228	3,758	-1549%	17,386	21,518	-23.8%
11	42,607	27,284	36.0%	4,864	5,604	-15.2%
12		501		19,474	22,687	-16.5%

Table 9 presents the sample size, R-squared, t-statistic, and p-value for the models for the baseline and integrated control conditions, respectively, for the fossil fuel prediction models. Light grey highlights indicate models where the outdoor weather had a weak or no relationship to the heating energy used—the fossil fuel use prediction models are poorly fitted to weather at sites 1, 7, 11, and 12. Notable and in darker grey in Table 9 is the positive relationship between temperature and energy use at sites 1, 8, and 10, suggesting that the colder the temperature, the less the legacy system is used.

Table 9. Fossil Fuel Heating Prediction Model Statistics

	FOSSIL FUEL Heating Use Prediction							
	Baseline				Integrated Control			
Site No.	Sample Size (Days)	R-squared	t-statistic	p-value	Sample Size	R-squared	t-statistic	p-value
1	41	0.03	-1.11	0.28	119	0.00	0.16	0.87
2	116	0.75	-18.35	0.00	209	0.62	-18.29	0.00
3	305	0.62	-22.21	0.00	89	0.80	-18.56	0.00
4	18	0.61	-4.96	0.00	100	0.57	-11.44	0.00
5	92	0.55	-10.55	0.00	125	0.66	-15.28	0.00
6	Not evaluated							
7	12	0.20	-1.57	0.15	6	0.11	-0.69	0.53
8	n/a	n/a	n/a	n/a	7	0.18	1.06	0.34
9	11	0.83	-6.62	0.00	9	0.87	-7.00	0.00
10	4	0.86	3.47	0.07	3	0.17	0.45	0.73
11	19	0.08	-1.23	0.23	14	0.04	-0.74	0.48
12	n/a	n/a	n/a	n/a	11	0.04	-0.62	0.55

Table 10 provides statistics for the electricity use models. Where separate electricity use models were used for mild and cold temperatures, the statistics for each model are provided. The electricity use prediction models for the total or the mild temperature bin during the baseline condition are poorly fitted to weather, though still significant (p>= 0.05), at sites 3, 4, and 7, and indicated in light grey. Where a separate cold weather model was used, model fits were always poor; however, the separate models were chosen in these cases because of the overall improvement to the predictions. The relative magnitude of the mild weather model's t-statistics conveys the importance of temperature to the amount of electricity used at these temperatures.

Table 10. Electric Heating Prediction Model Statistics

Site No.	ELECTRICTY Heating Use Prediction							
	Baseline (mild/cold)				Integrated Control (mild/cold)			
	Sample Size (Days)	R-squared	t-statistic	p-value	Sample Size	R-squared	t-statistic	p-value
1	85	0.63	-11.77	0.00	195	0.70	-21.07	0.00
2	104/26	0.82/0.02	-21.81/-0.69	0.00/0.50	213/13	0.76/0.08	-25.76/-0.98	0.00/0.35
3	168/83	0.33/0.02	-8.97/1.41	0.00/0.16	69/51	0.88/0.00	-21.81/-0.49	0.00/0.63
4	3/16	0.75/0.10	-1.71/-1.28	0.34/0.22	100	0.61	-12.42	0.00
5	92	0.44	-8.33	0.00	171	0.49	-12.85	0.00
6	Not evaluated							
7	12	0.33	-2.24	0.05	12	0.74	-5.37	0.00
8	66	0.44	-7.07	0.00	65	0.47	-7.41	0.00
9	11	0.47	-2.83	0.02	9	0.72	-4.20	0.00
10	49	0.76	-12.15	0.00	14/18	0.85/0.47	-8.14/-3.78	0.00/0.00
11	19	0.66	-5.79	0.00	14	0.46	-3.18	0.01
12	17	0.89	-10.95	0.00	34	0.94	-21.51	0.00

3.2.2 Site Evaluations

3.2.2.1 Site 1

The trend in results from site 1 is as expected. With the integrated controller enabled, fossil fuel energy was reduced (although the magnitude of savings is small due to lack of use), heat pump energy increased (although only slightly), and total heating energy was lower. For this site we have a robust data set, though the lower temperature range was somewhat limited and there was limited fossil fuel system use to evaluate.

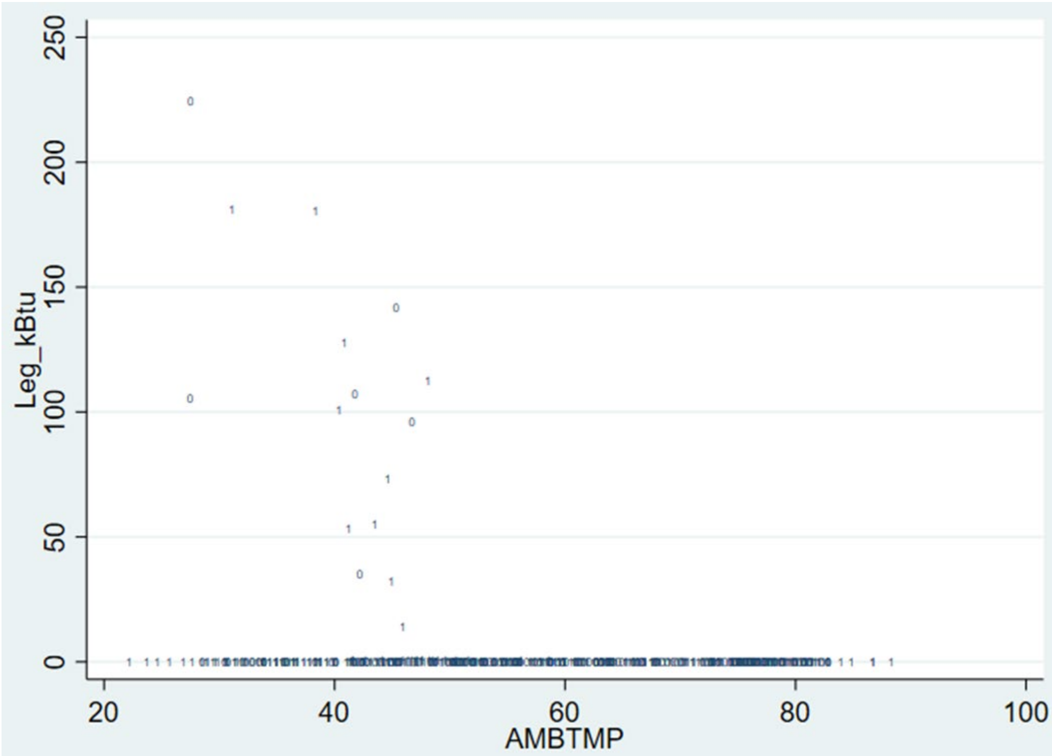
The predicted total heating energy use for the daily TMYx temperature range of 26°F to 62°F was 7,149 kBtu for the baseline condition and reduced to 6,036 kBtu for the integrated control condition, for a savings of 15.6%. The model strengths for the total use evaluation are both moderately low, with outdoor temperature explaining just over 50% of the total heating energy use, though the temperature variable is statistically significant for both models ($t[91] = -9.77$, $p = 0.00$ and $t[223] = -15.57$, $p = 0.00$, for the baseline and integrated control models, respectively).

The predicted fossil fuel use at this site decreased from 2,159 to 968 kBtu for the integrated control condition, for a savings of 55.2%. However fossil fuel system use is small, and shows no relationship to outdoor weather, upon which the prediction model is based. Coincident with the fossil fuel savings w as a slight increase in electric heating, which rose from 4,687 to 4,843 kBtu, or 3.3%, with much stronger statistical models backing these results (R^2 = 0.63, (t[84] = -11.77, p = 0.00 and R^2 = 0.70, t[194] = -21.07, p = 0.00 for the baseline and integrated control, respectively).

Despite the poor model strength for the fossil fuel regressions, the separate fuel predictions align well with the total use predictions. The sum of the energy use predicted by the fossil fuel and electric models is 95.8% of the total heating prediction for the baseline condition and 96.3% for the integrated control condition.

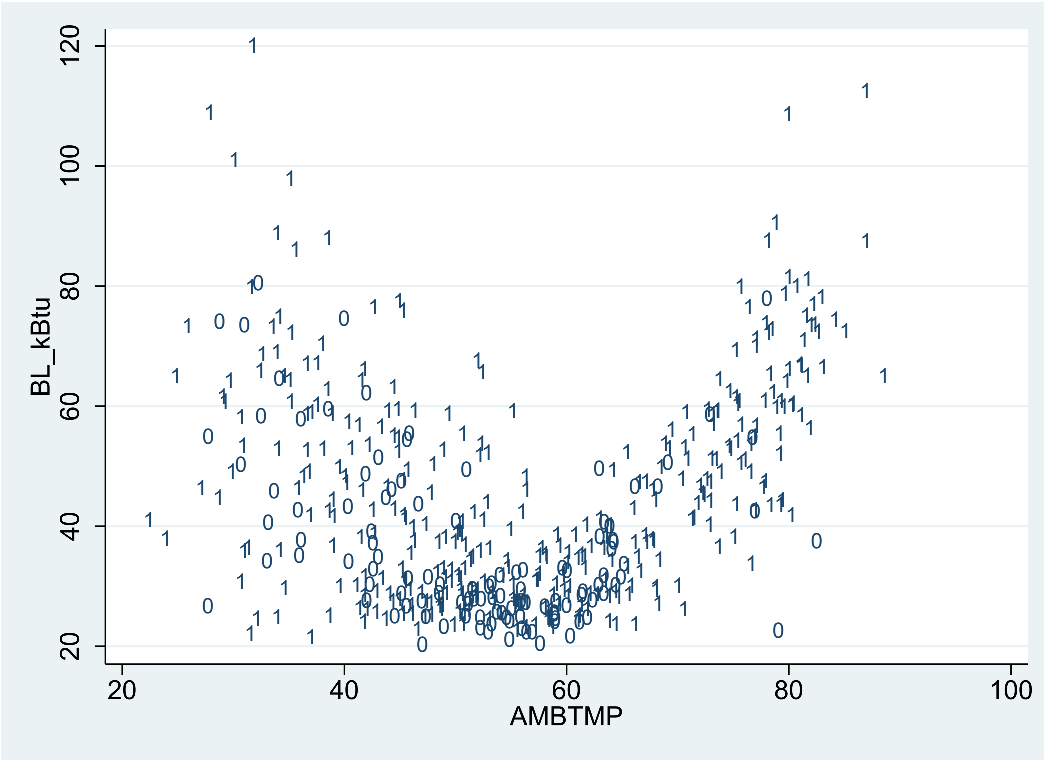
One big weakness in this evaluation is the lack of data for the fossil fuel system, due to lack of use for both conditions. Figure 5 plots the daily total fossil fuel kBtu on the Y-axis (Leg_kBtu) against daily average outdoor temperatures on the X-axis (AMBTMP). Note relatively few instances of operation of the fossil fuel system, during both baseline (0) and the integrated control (1) conditions. The data shows that the fossil fuel system is more often not used for the same temperatures for which there is recorded use, which explains the modeling difficulty. It appears that occupants prefer using the heat pump exclusively, with some rare exceptions. It also appears that a lack of outdoor temperatures below 15°F resulted in minimal operation of the fossil fuel system via the integrated controller outdoor changeover temperature feature.

Figure 5. Site 1 Daily Fossil Fuel Use against Outdoor Temperature



A caveat to the findings for site 1 is that we suspect some electrical space conditioning energy that was not monitored. Figure 6 plots the daily total electric energy use for baseload: the measured total building load minus all space conditioning monitored. The shape of the curve and its magnitude indicate the baseload captures electric equipment used for both heating and cooling, and during both conditions. Two or three space heaters were observed at this property, but not able to be monitored.

Figure 6. Site 1 Baseload Energy Use Indicating Space Heating Not Captured



3.2.2.2 Site 2

The trend of the results from site 2 were as expected, though overall energy use differences between baseline and integrated control conditions were minimal. Fossil fuel use was slightly reduced and heat pump use slightly increased during the integrated control condition. The homeowner claimed that she adjusted the setpoint manually through the device frequently, in either baseline or integrated control period, which might result in small energy use differences. For this site we have a robust data set in terms of sample size, though data at the low end of the temperature range is somewhat limited.

The predicted heating energy use for the daily TMYx temperature range of 25°F to 68°F was 35,745 kBtu for the baseline condition and was essentially unchanged at 35,456 kBtu for the integrated control condition. Both models are strong and outdoor temperature is statistically significant ($R^2 = 0.82$, $t[116] = -22.80$, $p = 0.00$ and $R^2 = 0.74$, $t[194] = -23.65$, $p = 0.00$, for baseline and integrated control, respectively).

The predicted fossil fuel system use at this site decreased slightly from 29,437 to 28,438 kBtu for the integrated control condition, for a savings of 3.4%. The trend between energy use and temperature is fairly strong to moderate and the temperature variable is statistically significant for both models ($R^2 = 0.75$, $t[115] = -18.35$, $p = 0.00$ and $R^2 = 0.62$, $t[208] = -18.29$, $p = 0.00$ for the baseline and integrated control, respectively).

Coincident with this fossil fuel use reduction was a slight increase in electricity used for heating, which rose slightly from 6,739 to 6,961 kBtu, or 3.3%. For this site it was useful to model electricity use separately for cold and mild temperatures. The mild weather model applied to most of the heating days. The colder model applied to days with daily average temperatures below 37°F for the baseline condition and below 32°F for the integrated control condition. The mild weather models are both strong and the temperature variable significant ($R^2 = 0.82$, $t[103] = -21.81$, $p = 0.00$ and $R^2 = 0.76$, $t[212] = -25.76$, $p = 0.00$ for the baseline and integrated control, respectively). There was no relationship between outdoor temperature and electricity use during cold weather. While outdoor temperature is not a significant predictor of heat pump energy use, the average electricity use for heating during the cold weather period is still an important component of total heat pump energy use.

Although there is difficulty modeling the electricity use during colder weather, the sum of the energy use predicted by the fossil fuel model and the two electric models aligns well with the energy use predicted by the total heating model. The sum of the three model predictions is 101.2% of the total heating prediction for the baseline condition, and 99.8% for the integrated control condition.

Site 2 also presents evidence of a small amount of unmonitored electric space heating during both conditions. Confirmation was made with the homeowner that a space heater was used "constantly" while she was home working in her home office.

3.2.2.3 Site 3

Results from site 3 indicate that fossil fuel system energy use was reduced during the integrated controller condition. However, unexpectedly, heat pump use also decreased under the same condition. For this site we have a fairly robust data set in terms of sample size, though the temperature range low is somewhat limited.

The total predicted heating energy use for the daily TMYx temperature range of 24°F to 74°F was 50,241 kBtu for the baseline condition and reduced to 43,297 kBtu by the integrated control condition, for a savings of 13.8%. The model strengths for the total use evaluation are both strong and temperature is statistically significant (R^2 = 0.71, $t[241] = -24.17$, $p = 0.00$ and R^2 = 0.82, $t[94] = -20.48$, $p = 0.00$, for baseline and integrated control, respectively).

The predicted fossil fuel system energy at this site decreased from 48,406 to 40,552 kBtu for the integrated control condition, for a savings of 16.2%, with a moderately strong statistical model for the baseline (R^2 = 0.62) and strong model for the integrated controller condition (R^2 = 0.80). Temperature is statistically significant in both models ($t[304] = -22.21$, $p = 0.00$ and, $t[88] = -18.56$, $p = 0.00$ for baseline and integrated control, respectively).

Coincident with reduced fossil fuel system energy is an unexpected decrease in electric heating energy during the integrated controller condition, from 3,025 to 2,819 kBtu, or 6.8%. For this site it was useful to model electricity use in separate cold and mild temperature bins for both conditions. Modeling strength for the baseline condition during mild weather is relatively poor, but the temperature variable is statistically significant (R^2 = 0.33, $t[167] = -8.97$, $p = 0.00$). For the integrated control condition, a strong fitted model with statistically significant temperature variable applied to the mild weather with daily average temperatures below 48°F (R^2 = 0.88, $t[68] = -21.81$, $p = 0.00$). The cold weather models for both conditions show poor trends to temperature.

Despite the difficulty modeling some of the electricity use, the sum of the energy use predicted by the fossil fuel and electric models aligns well with the prediction from the total use model. The sum of the energy use from the three model predictions is 102.4% of the total heating prediction for the baseline and 100.2% for the integrated control condition.

No unmonitored space heating was observed in the data nor reported by the homeowner.

3.2.2.4 Site 4

The results from site 4 are as expected—fossil fuel system use was greatly reduced and heat pump use slightly increased during the integrated control condition. The data set for this site is robust. However, before the second winter of the study, the furnace failed and the unit remained off until the study ended. This results in an evaluation limited to more mild temperatures. Also monitored at this site was some uncontrolled electric heating.

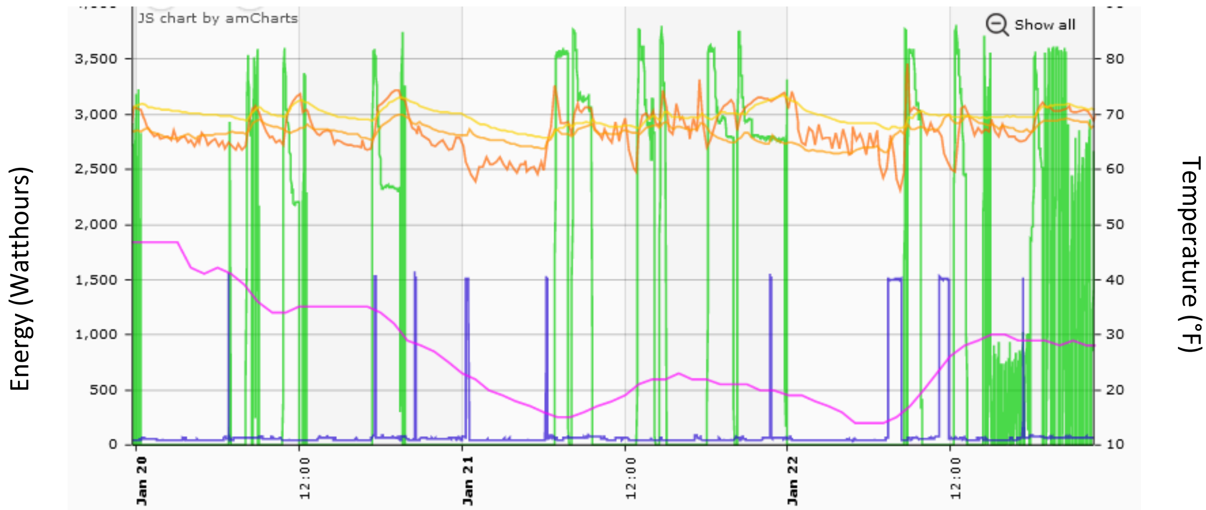
The predicted total heating energy use for the daily TMYx temperature range of 35°F to 61°F was 52,174 kBtu for the baseline condition and reduced to 35,680 kBtu for the integrated control condition, for a savings of 31.6%. The models for the total use evaluation have mildly strong trends to weather and temperature is statistically significant ($R^2 = 0.72$, $t[17] = -6.67$, $p = 0.00$ and $R^2 = 0.66$, $t[89] = -13.18$, $p = 0.00$, for baseline and integrated control, respectively).

The predicted fossil fuel system use decreased at this site from 46,903 to 30,315 kBtu for the integrated control condition, for a savings of 35.4%. Both models have moderate fits to weather and the temperature variable is statically significant ($R^2 = 0.61$, $t[17] = -4.96$, $p = 0.00$ and $R^2 = 0.57$, $t[99] = -11.44$, $p = 0.00$, for baseline and integrated controller, respectively). Coincident with this fossil fuel reduction was an increase in electric heating, from 3,448 to 5,033 kBtu, or 45.9%. For site 4, there was a benefit to generating separate cold and mild temperature models during the baseline condition. The trend between electricity use and temperature was strong for the mild temperature baseline condition ($R^2 = 0.75$) though poor for the cold temperature baseline condition ($R^2 = 0.10$), and weather was not statistically significant in either model. The weather trend was moderately strong for the single integrated control model ($R^2 = 0.61$) and the temperature variable is statistically significant ($t[99] = -12.42$, $p = 0.00$). Despite the poor weather fits of one of the baseline models, the separate fuel predictions align very well with the total use predictions. The total of the three model predictions is 96.5% of the total heating prediction for the baseline, and 99.1% for the integrated control condition.

While the failure of the fossil fuel system was unfortunate for purposes of this experiment, it is telling that the occupants were able to live comfortably during this time. Figure 7 provides the heat pump and window unit use at site 4 during a few days of the coldest weather during furnace failure. With exterior temperatures dropping below 20°F, the heat pump was operating. Monitored energy use of the circuit assigned to the window unit increased during the fossil fuel system failure. The temperature in the living room (darker orange) was allowed to dip below 60°F a few times, while the bedroom temperatures (yellows) generally remained near 70°F with a couple of drifts down to the mid-60s (°F).

Figure 7. Site 4 ASHP and Window Unit Operation during Furnace Failure

ASHP in green, window unit in blue, interior temperatures in orange shades, and exterior temperature in pink.



Data indicate there may be a small amount of uncaptured heating energy at this site during both test conditions.

3.2.2.5 Site 5

Results from site 5 indicate the use of the fossil fuel system was reduced for the integrated control condition. Unexpectedly, the heat pump use also decreased during this period. The data set for this site is robust. One caveat to the baseline condition at Site 5 is that the occupants kept the scheduling and geofencing function during the baseline period. Thus, the baseline period potentially experienced some of the energy use savings of these features, thereby reducing the reported savings.

The predicted total heating energy use for the daily TMYx temperature range of 21°F to 61°F was 19,949 kBtu for the baseline condition and reduced to 17,936 kBtu for the integrated control condition, for a savings of 10.1%. The models for the total use evaluation show mildly strong trends to weather, and temperature is statistically significant ($R^2 = 0.62$, $t[159] = -12.12$, $p = 0.00$ and $R^2 = 0.68$, $t[142] = -17.45$, $p = 0.00$, for baseline and integrated control, respectively).

The predicted fossil fuel use at this site decreased from 16,354 during the baseline condition to 14,606 kBtu during the integrated control condition, for a savings of 10.7%. The baseline model shows weather has marginal statistical strength ($R^2 = 0.55$), while the model for the integrated control is a bit stronger ($R^2 = 0.66$). Temperature is statistically significant for both models ($t[91] = -10.55$, $p = 0.00$ and, $t[124] = -15.28$, $p = 0.00$, for baseline and integrated control, respectively). Coincident with this fossil fuel savings was a decrease in electric heating, from 4,835 to 3,538 kBtu, or 26.8%. Electricity use trend to weather is moderately weak in both models; however, temperature is statistically significant ($R^2 = 0.44$, $t[91] = -8.33$, $p = 0.00$ and $R^2 = 0.49$, $t[170] = -12.85$, $p = 0.00$, for baseline and integrated control, respectively).

The separate fuel predictions align relatively well with the total use predictions. The total of the fuel predictions for the separate fuel models is 106.2% of the total heating prediction for the baseline, and 101.2% for the integrated control.

There is no indication of uncaptured heating energy at this site.

3.2.2.6 Site 6

Unfortunately, we were unable to evaluate site 6 given a short monitoring period with two large data gaps. Difficulty monitoring this site delayed data collection for about one month from installation, until December 28, 2021. Data were then collected for nearly a month with the home in the integrated control test configuration. The SiteSage energy monitor stopped connecting via its gateway on January 22, 2022. Data collection resumed on March 16, 2022 with the home running it its baseline test configuration. However, the outdoor temperatures by then were much warmer than for the integrated control test, thus no operational comparison was possible.

3.2.2.7 Site 7

The evaluation at site 7 was difficult due to very limited data. The home was monitored for one winter, but part way through that winter the fossil fuel system failed. This home is renter-occupied, and occupancy change is in question due to inconsistent use patterns within the same test condition. The evaluation is limited to about two weeks with similar weather before and after a transition from the integrated control condition to baseline. The limited data show the results are as expected, in that fossil fuel use was reduced during the integrated control condition. However, unexpectedly, heat pump use also decreased.

The predicted heating energy use for the daily TMYx temperature range of 24°F to 50°F was 47,251 kBtu for the baseline condition and was reduced to 34,282 kBtu for the integrated control condition, for a savings of 27.4%. The baseline model shows a poor trend between weather and total heating use ($R^2 = 0.21$), and temperature is not significant. The trend for the integrated control model is not much stronger, but temperature is statistically significant ($R^2 = 0.41$, $t[11] = -2.62$, $p = 0.03$).

The predicted fossil fuel system use at this site decreased from 40,677 to 24,119 kBtu during the integrated control condition, for a savings of 40.7%. Models for both conditions show the energy used has a poor relationship to the outdoor temperature ($R^2 = 0.20$ and $R^2 = 0.11$, for baseline and integrated controller, respectively) and temperature is not statistically significant. Heat pump heating also decreased during integrated control, from 6,574 to 5,820 kBtu, or 11.5%. The trend between electricity use and weather for the baseline condition is weak ($R^2 = 0.33$), while that for the integrated control is moderately strong ($R^2 = 0.74$). Temperature is statistically significant for both models ($t[11] = -2.24$, $p = 0.05$ and, $t[11] = -5.37$, $p = 0.00$, for baseline and integrated control, respectively).

Although the trend to weather is weak for much of the modeling, the separate fuel predictions for the baseline condition align perfectly with the total prediction (40,677 kBtu for fossil fuel plus 6,547 kBtu for electricity = 47,251 kBtu total). However, the separate fuel use predictions for the integrated control condition period fell short, at 87.3% of the total prediction. This suggests that either the fossil fuel or electricity use reductions, or both, are less than indicated.

There is no indication of unmonitored space heating at this site.

3.2.2.8 Site 8

The results from site 8 were not as expected. The fossil fuel system was not used during baseline and had limited use during the integrated control condition. The integrated controller programmed outdoor changeover temperature setting eliminating heat pump use was 23 °F at this site, in contrast to the 15 °F changeover used at all the sites previously evaluated. Overall, slight negative savings were tabulated during the integrated control condition. Common to most of the sites with negative savings, the heat pump retrofit involved installation of several indoor ductless heads (in this case five), resulting in a complete ductless retrofit, compared to installation of a ductless supplement, as experienced for sites with fewer (1-2) indoor heads. For this site the temperature range evaluated is limited.

The predicted total heating energy use for the daily TMYx temperature range of 21°F to 55°F was 11,749 kBtu for the baseline condition and increased to 12,129 kBtu for the integrated control condition for negative savings of 3.2%. The similarities between weather and total use for both models are moderately low, though temperature is statistically significant ($R^2 = 0.44$, $t[65] = -7.07$, $p = 0.00$ and $R^2 = 0.48$, $t[64] = -7.55$, $p = 0.00$, for baseline and integrated control, respectively).

There were seven days of fossil fuel system use during the integrated controller condition, apparently triggered by the advanced controller changeover temperature setting when the system would not otherwise have been used according to baseline data. Fossil fuel use during the integrated control condition was minimal (397 kBtu). Energy used does not trend well with weather ($R^2 = 0.18$), and temperature is not statically significant. The predicted electricity heating was 11,749 kBtu for the baseline (the same model as the total since there was no gas use) and 11,526 kBtu for the integrated control condition for slight savings of 1.9%. The energy used shows mild correspondence with weather, and temperature is statistically significant ($R^2 = 0.47$, $t[64] = -7.41$, $p = 0.00$) for the integrated control model. The total of the split fuel predictions for the integrated controller condition are 98.3% of that predicted with the total energy use model.

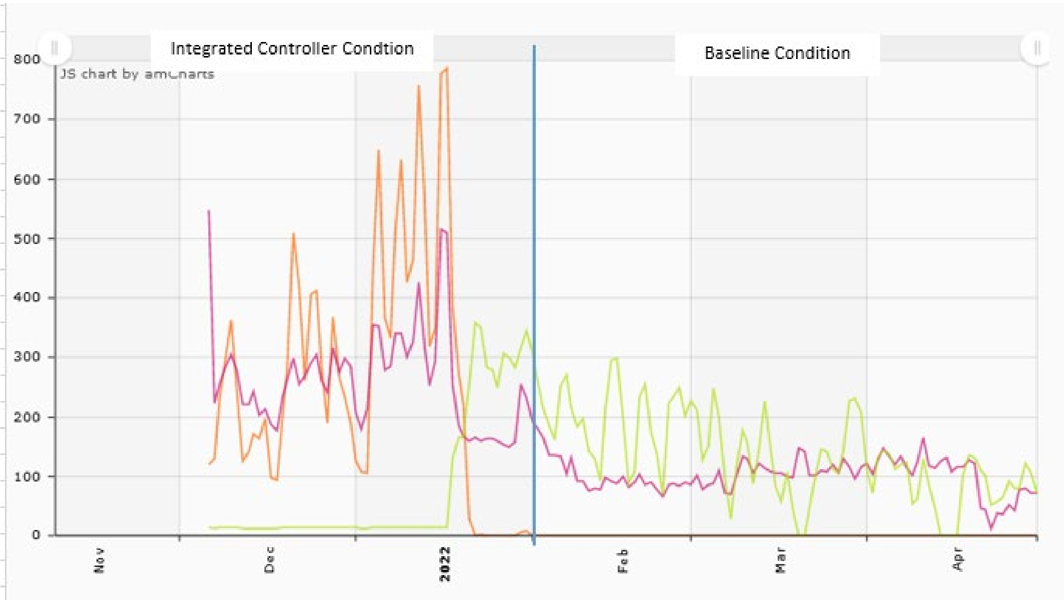
There is no indication of unmonitored space heating at this site, which was confirmed by the occupant.

3.2.2.9 Site 9

The evaluation at site 9 was severely limited due to a change in occupancy and behavior. Initially, the fossil fuel system was not used. Upon departure of an occupant, use of one of the heat pumps was abandoned and regular fossil fuel system use began. In addition, the second heat pump was used much more modestly than it had been before the occupancy change. Figure 8 shows the trends. The blue vertical line indicates the test condition transition from integrated control to baseline. This change occurred prior to obtaining baseline data. With no comparable baseline condition, the period with both heat pumps in use was excluded from the evaluation. This limited the evaluation to nine days of baseline and 11 days for the integrated controller. Thus, the temperature range evaluated is very limited.

Figure 8. Site 9 ASHP and Air Handler Power

Orange = heat pump 1; pink = heat pump 2, green = furnace air handler; Y-axis = Watthours



The results from the limited data evaluation at site 9 were not as expected—both fossil fuel and electricity heating use increased for the integrated control condition. It is noteworthy that the indoor temperatures measured at this site were higher, on average, during integrated control than during the baseline period. Although the outdoor temperatures were not identical between periods, the magnitude of the difference in temperatures indicates possible occupancy "take back," negatively impacting the energy use during integrated control testing.

The predicted heating energy use for the daily TMYx temperature range of 22°F to 38°F was 38,535 kBtu for the baseline condition and increased to 50,227 kBtu for the integrated control condition, for negative savings of 30.3%. The trend of weather to total heating energy used is very strong for both models and temperature is statistically significant ($R^2 = 0.83$ $t[10] = -6.60$, $p = 0.00$ and $R^2 = 0.88$, $t[8] = -7.01$, $p = 0.00$ for baseline and integrated control, respectively).

The predicted fossil fuel use at this site increased from 36,701 to 47,849 kBtu for the integrated control condition for a negative savings of 30.4%. Both models show a strong relationship between energy used and weather, and temperature is statistically significant ($R^2 = 0.83$, $t[10] = -6.60$, $p = 0.00$ and $R^2 = 0.88$, $t[8] = -7.01$, $p = 0.00$, for baseline and integrated control, respectively). The heat pump addressed a small fraction of load; electric heating use increased from 1,834 to 2,378 kBtu, or negative 29.7%. The trend between weather and electricity use is moderately weak for baseline condition ($R^2 = 0.47$), while that for the integrated control condition is moderately strong ($R^2 = 0.72$). Temperature is statistically significant in both models ($t[10] = -2.83$, $p = 0.02$ and $t[8] = -4.20$, $p = 0.00$ for baseline and integrated control, respectively). The separate fuel predictions align perfectly with the total-use prediction for both the baseline and integrated control.

The fossil fuel system fuel valve operation was not monitored at this site. In place of the operation, run time was estimated with the monitored air handler fan data. Total building power was also not monitored at this site, so an evaluation for potential space heating not otherwise captured was not possible.

3.2.2.10 Site 10

Results from site 10 were not as expected. The data set for site 10 is somewhat limited due to a short monitoring period, and negative savings were tabulated. Similar to site 8, the retrofit at this site involved installation of five indoor ductless heads.

The predicted heating energy use for the daily TMYx temperature range of 27°F to 55°F was 19,357 kBtu for the baseline condition and increased to 22,888 kBtu for the integrated control condition for a negative savings of 18.2%. The models for the total heating use prediction have a moderate fit to weather, and temperature is statistically significant ($R^2 = 0.64$, $t[48] = -9.11$, $p = 0.00$ and $R^2 = 0.61$, $t[22] = -5.30$, $p = 0.00$, for baseline and integrated control, respectively).

The fossil fuel system was used only a few days during each condition, and energy use was limited. The predicted fossil fuel use at this site increased from 228 to 3,758 kBtu during the integrated control condition. The integrated controller appears to have triggered the fossil fuel system when it would not otherwise have been used. Both models show a positive trend between fossil fuel energy use and temperature, meaning that, for the days the fossil fuel system was engaged, less energy was used during colder weather—contrary to what is expected. This finding points to the poor ability to predict energy use with such small samples.

Electric heating also increased during the integrated control condition, from 17,386 to 21,518 kBtu for a negative savings of 23.8%. The electricity used during the baseline condition trends well with weather (R^2 = 0.76). For this site, it was useful to model electricity use in separate cold and mild temperature bins for the advanced control condition only, where a statically strong model (R^2 = 0.85) applies to the mild weather, when the average daily average temperature is above 34 °F. The model fit for the colder weather is relatively weaker (R^2 = 0.47), but better than most. Temperature is statistically significant in all three models ($t[48] = -12.15$, $p = 0.00$; $t[13] = -8.14$, $p = 0.00$ and $t[17] = -3.78$, $p = 0.00$, for baseline, integrated control mild, then cold, respectively). The separate fuel predictions for the baseline are 91.0% of the baseline total-use regression and 110.4% of the integrated controller total-use prediction, indicating that the negative savings for either the fossil fuel system or electricity use, or both, are overstated.

Total power was not captured at this site, so we are unable to look for an indication of space heating use not otherwise captured. However, the occupant reported there is no other heat source at this site.

3.2.2.11 Site 11

The site 11 results were as expected—the fossil fuel system use was greatly reduced and heat pump use increased for the integrated control condition. Despite the high outdoor changeover temperature setting at this site (23 °F), savings were still experienced during the integrated control condition. Even though this site has five indoor ductless heads, the fossil fuel system was still used at mild temperatures where savings were observed. The magnitude of electricity used for heating is small compared to other sites with several indoor heads such as site 8 and site 12. Also notable is that the control at this site did not have an indoor droop feature like other sites. The evaluation at this site was limited to 22 days of baseline condition and 14 days of integrated control condition. Further, only mild weather was evaluated.

The predicted total heating energy use for the daily TMYx temperature range of 39°F to 57°F was 47,470 kBtu for the baseline condition and reduced to 32,887 kBtu during the integrated control condition for a savings of 30.7%. Neither model shows a good fit between energy use and outdoor temperature (R^2 = 0.13 and R^2 = 0.14 for the baseline and integrated control, respectively) and temperature is not statistically significant for the baseline model, and only marginally for the integrated control model.

The predicted fossil fuel system use at this site decreased from 42,607 to 27,284 kBtu for the integrated control condition for a savings of 36.0%. Again, neither regression has a trend to weather. ($R^2 = 0.08$ and $R^2 = 0.04$ for the baseline and integrated control, respectively), and temperature is not statistically significant. Coincident with this fossil fuel savings was an increase in electric heating, which rose from 4,864 to 5,604 kBtu, or 15.2%. In contrast to the fossil fuel modeling, temperature is more strongly tied to electricity use and statistically significant (R2 = 0.66, $t[18] = -5.79$, $p = 0.00$ and R2 = 0.46, $t[13] = -3.18$, $p = 0.01$ for the baseline and integrated control, respectively). Despite the poor model strength for the fossil fuel regressions, the separate fuel align perfectly with the total use predictions.

Fuel valve operation was not monitored at this site to estimate runtime of the fossil fuel system. Run time was instead estimated with the monitored air handler data.

3.2.2.12 Site 12

The results from site 12 were not as expected—the fossil fuel system was not used during baseline and rarely used during the integrated control condition. Overall, negative savings were tabulated during the integrated control condition. As with other sites showing negative savings, the retrofit at this site involved multiple indoor heat pump heads (seven). The evaluation of this site suffers from data loss due to monitoring equipment issues. The baseline condition is limited to 17 days and the integrated control condition 34 days. Unsurprisingly, the temperature range is thus limited.

The predicted total heating energy use for the daily TMYx temperature range of 15°F to 56°F was 19,473 kBtu for the baseline condition and increased to 23,035 kBtu for the integrated control condition for a negative savings of 18.3%. Outdoor temperature has a tight fit to total heating energy and is statistically significant for both models ($R^2 = 0.89$, $t[16] = -10.95$, $p = 0.00$ and $R^2 = 0.82$, $t[33] = -11.80$, $p = 0.00$, for baseline and integrated control, respectively).

Fossil fuel use during the integrated control condition was minimal at 501 kBtu, though apparently triggered by a higher changeover temperature setting (23°F), engaging the fossil fuel system during the integrated control condition, when it would not have otherwise been used. The model for the fossil fuel use under the integrated control condition does not correspond to outdoor temperature ($R^2 = 0.04$), and outdoor temperature is not statically significant. The predicted electric heating was 19,474 kBtu for the baseline (the same model as the total since there was no gas use) and 22,687 kBtu for the integrated control condition for a negative savings of 16.5%, though the energy use change appears to be unrelated to the testing of the integrated controller. The weather to energy use trend is in the integrated control model (R^2 = 0.94, $t[33]$ = -21.51, p = 0.00). The total of the split fuel predictions is very close to that predicted with the total energy use model for the integrated control condition at 100.7%.

There is an indication of potentially a small amount of unmonitored space heating at this site.

3.2.3 Conclusions

Twelve New York State residences retrofitted with a variety of ductless ASHP system configurations—all serving to offset the use of an existing fossil fuel system—were selected for evaluation of energy-use changes related to the installation a controller coordinating operation of the two independent heating systems. The total energy use, heating energy use, and interior temperatures were monitored at each site during some period between January 2020 through winter 2022. Data were collected during a baseline condition with the two independent systems running without use of the integrated controller, and during the integrated control condition. The manufacturer of the control and control integration setup varied among the sites, differing in the droop and outdoor changeover temperatures.

Data collected from each site were filtered for similar temperature ranges for each condition at each site. Complete, fuel specific, heating-energy use regression models (linear) were created for each condition, so that energy use could be normalized to the same outdoor weather. Some sites have robust data and strong confidence in findings are indicated, while the analyses at other sites suffer from limited data sets and results are less reliable. Given the uniqueness of the system and equipment setup at each site, the evaluation is understood as a case study. Potential savings for heating energy for the integrated control condition are indicated for the temperature ranges evaluated at each site; therefore, findings are presented by site and not as an overall average.

Total, weather-normalized, heating energy use savings experienced during the integrated control condition ranged from -30.3% to 31.6%. Aside from three sites with essentially no fossil fuel system use during the baseline condition, the fossil fuel heating use savings tabulated during the integrated control condition was positive as expected, ranging from 3.4% to 35.4%, except for one site with negative savings of 30.4%. The predicted heating electricity use increased during integrated control, as expected, at seven sites ranging from 3.3% to 29.7%, while the remaining four sites showed savings ranging from 1.9% to 26.8%.

Results indicate that the use of an integrated control may or may not result in a decrease in fossil fuel use. Two important factors affect whether fossil fuel savings can be expected. One is how the occupants manually control the two independent systems, without an integrated control in place. This seems to be correlated with whether the ASHP retrofit constitutes a nearly complete ductless retrofit or serves as a more modest supplement to the legacy fossil fuel system. The other is how the specific inputs to the integrated controller are configured.

Across the 11 sites for which an evaluation could be conducted, seven had positive fossil fuel system savings during the integrated control condition. Six of these seven with positive fossil fuel savings had a modest number of indoor ASHP heads: three sites had one head, two sites had two heads, and one site had three heads. Site 1 had a large percent savings but absolute use and savings were small. Site 2 had larger fossil fuel use but small percent savings. Positive total heating-energy savings during the integrated control condition was also tabulated at all seven of these sites. While a corresponding negative electricity savings was expected at these sites, results show more variability with negative savings tabulated at only four of the seven.

Four of the five sites with larger numbers of ASHP heads, ranging from four to seven, had either no fossil fuel use during the baseline period, or otherwise tabulated negative savings for the integrated control period, with site 11 (five heads) as the exception with positive fossil fuel savings. At one of these sites with negative savings, site 9 (4 heads), an increase in the interior temperature during integrated control was observed, which may have eroded savings at this site. Still, it appears likely that with no real-time feedback on energy costs, occupants of homes that undergo a more complete ductless system retrofit are more likely to rely on the ASHP than the fossil fuel system because of adequate ASHP capacity. Savings in electricity used for heating was y-negative for four of the sites with larger numbers of ASHP heads, and essentially unchanged for the fifth.

In addition to variations in the number of ASHP heads installed at each site, there were differences in the integrated controller setup, specifically, different outdoor changeover temperatures were programmed to deactivate the heat pump. At six of the seven sites where the outdoor changeover temperature was set to 15°F, fossil fuel heating savings was tabulated during the integrated control condition. At three of these sites, the fossil fuel system savings coincided with an increase in electric heating, although in three other cases heat pump activity unexpectedly decreased during the integrated control condition.

At three of the four sites where the integrated control condition experienced negative savings for both fossil fuel heating and total heating use overall (in addition to a larger number of indoor ASHP heads), a higher outdoor changeover temperature (23ºF) was set. This restricted heating to the fossil fuel system during temperatures when baseline data indicated the fossil fuel system would not have engaged. This changeover temperature setting appears to be higher than ideal for reducing fossil fuel use and may increase fossil fuel use instead. While site 9 also had negative savings during integrated control with a 15ºF changeover temperature, we have an unfortunate, large truncation of data due to occupancy changes that coincide with abandoning one of the heat pumps and drastically reducing use of the second. There was a fourth site (site 11) where, despite the higher outdoor changeover temperature setting of 23ºF, both fossil fuel heating and total heating were reduced during the integrated control condition. The fossil fuel system was used often at more mild temperatures, relative to other sites, and savings were observed at this mild temperature range. A lower changeover setting would potentially generate even greater savings during the integrated control condition at this site. (However, the modeling strength at the site is particularly poor.)

3.3 Survey Results

This section presents the project team's summaries from the results of customer surveys. Participating residents were interviewed at the conclusion of data monitoring. At some of these sites the team also followed up by phone with additional questions. The interview questions are provided in appendix A.

Most residents interviewed were satisfied with the thermal comfort of the new system. While interview results indicate overwhelming satisfaction of the air source heat pump system, most residents showed less satisfaction with the central heating system after the integration. The homeowner at site 3 reported overheating situations at his house during the data monitoring. The situation was improved after the team suggested lowering the central heating setpoint. At site 10, the boiler never turned on after the retrofit, which the team suspected could be caused by boiler failure or integrated controller malfunctioning.

Half of the residents were dissatisfied with the integrated control system. A few residents complained that the integrated control system turned the heat pump on or off without input and did not turn on the legacy system when needed. The homeowner at site 5 reported an incident when the integrated controller sent signals to the heat pump indoor head continuously all night. Resideo discovered a service shutdown, and the issue was resolved. Resideo discontinued the software update during the project and caused inconvenience in initial setting up of the integrated control system.

Interview results showed that the energy cost after retrofit is more than or as expected by most residents. Because electricity is more costly per unit of energy than natural gas in the New York City region, more energy cost is expected, even though the newly installed heat pumps are efficient. Half of the residents adjusted their thermostat settings though they were asked not to change the settings during the study without notifying the project team.

4 Lessons Learned

4.1 Data Collection and Monitoring

We see three areas for improvement in this study regarding data collection and monitoring.

1. **Larger sample size.** There was much variation among the test sites in terms of the existing central system type, extent of the ASHP retrofit, and controller type and setup. A larger sample size would have better normalized results for these varying conditions, at the expense of added cost and project duration. Alternatively, with a small sample size, these conditions could have been controlled, although there are limitations to how closely conditions can be controlled in residents' homes over long periods of time.
2. **Longer monitoring periods with data for additional conditions**.
   - One winter historic data collection—Ideally, we would have monitored one winter with fossil fuel use only, prior to installation/use of ASHP.
   - Two winters of the two-system setup—One winter with the ASHP controlled independently and one winter with integrated control to allow collection of a full range of temperatures, especially including the coldest temperatures during both test conditions. This would have alleviated the need to flip-flop between conditions and allowed for full-seasonal heating use predictions, rather than just limited temperature ranges. Since those ranges differ from site to site, it prevents aggregating the data and results. In general, the data collection period for many of the sites was particularly short and the energy use predictions for individual sites are less statistically robust. Also, the ASHP and the integrated controller were new to the occupants, and it takes time for occupants to settle in on how they interact with new equipment, so longer data collection periods are warranted. For future studies, it would be interesting to have monitoring periods of different integrated control strategies; for example, one winter with outdoor changeover only and another winter with indoor droop only.
   - Given a longer test period, we could also have afforded a short-term test with tight control over occupant setpoints. This could provide insight into the impacts of setpoint changes coincident with the changes in controller, independent of occupant interactions.
3. **More diligent identification and monitoring of energy use of other heat sources.** At more than half of the project sites, there was evidence of unmonitored heat source or other electric use. Although electric space heating was confirmed at a few sites through follow-up phone calls with the residents, little of it was monitored. If heat sources other than the heat pump and the central system could be identified at the early stage and monitored through the course of the project, the data analysis results will be more accurate.

4.2 Design and Configuration

The biggest design challenge of the project was to select suitable control scenarios with qualified products. At the early stages of the project, through market research with assistance from the advisory panel, the project team ruled out some control scenarios including wired options for forced-air and hydronic systems and options using zone-controllers. Most of these options were ruled out due to the lack of a suitable product available. Some qualified products require complicated software configuration and/or add difficulties to installation; some products were not used because of high costs or discontinuation. Another reason why wired options were ruled out is aesthetic considerations and cost to conceal the wiring.

Another challenge of the integrated control design is configuring the control system correctly. There is no established industry standard for either the outdoor changeover temperature or the indoor droop. Therefore, these control settings were either based on recommendations of controller manufacturers (e.g., Resideo sites) or criteria of rebate program (e.g., DKN sites). At some sites, outdoor changeover temperatures were adjusted to increase boiler/furnace use, and indoor droop settings were adjusted for consideration of occupant comfort. Upon completion of the project, no complaints were related to the temperature settings.

4.3 Barriers

Cost: Even though the products with the highest prices on the market were not used in the project, the control products used are still expensive. Resideo and Flair products were donated by the manufacturers, which made most sites more economically feasible. Considering the work of wiring/networking and dealing with low-voltage lines, labor cost is also significant.

Quality: Some quality issues were reported during this project. The Wi-Fi controllers were highly dependent on the Internet connection. For example, connection issues at site 2 led to control disruption. Several sites reported the legacy system did not turn on when needed.

Service: No issues were reported with the newly installed high-efficiency heat pumps. Resideo controllers were discontinued, and its manufacturer ceased software update after the sites were installed, making future technical support on the software end difficult. Controller manufacturers denied responsibility for fixing controller issues while electrician and other installers were also reluctant to do repair, inspection, and other services. Because of the limited work scope and limited availability of skilled technicians, homeowners may have difficulty retaining regular service at reasonable costs.

Design: The lack of reliable and suitable products on the market added difficulties to designing integrated control systems. A well-sized heat pump design as well as refined control settings helped avoid critical system failures but did not necessarily lead to desired system performance when the controllers did not function as expected; for example, when they did not enable the legacy heating system when setpoint was met.

Savings/payback: Because electricity is more costly per unit of energy than natural gas in the NYC region, electrification often results in higher utility bills for space heating, even when heat pumps are operating efficiently. Data analysis results demonstrate that the integrated control alone may or may not result in energy savings. Theoretically, an ideal control product that delivers what it promises can lead to more energy savings, assuming less interference from occupants.

Awareness/education: As homeowner awareness and understanding of heat pumps is limited, integrated control is even more so. Half of these projects transitioned from heating primarily with hydronic or steam systems to heating primarily with warm air from heat pumps with legacy system as the secondary heat source. This heat source change resulted in perceived and sometimes actual differences in comfort (both positive and negative). Yet the interview results indicated overall satisfaction with the air source heat pump system. Benefits brought by integrated control, on the other hand, are not easily perceived by occupants. Residents, however, often felt limited by the control system since it was designed to work in an automatic manner rather than regulated freely by the occupants.

4.4 Homeowner Perceptions and Motivations

One underlying motivation for homeowners was the need to improve the comfort of their home. And most homeowners were happy with the new heat pump system, especially homes with window air conditioners (ACs) or a poorly maintained legacy system. Some homeowners liked the added controllers for features such as scheduling and geofencing; however, the controllers also brought problems like noise when sending signals and setpoints either too high or too low that were not initiated by the occupants. Homeowners are also concerned about the aesthetics and cleanliness of their home after the work is completed. Wireless controllers meet most homeowner's aesthetic expectation. All heat pump installation work was clean, and no related issue was discovered.

Homeowners reported finding no number to call and no party willing to take responsibility when issues arose with the controller. Contractors should take ownership and be the ones to contact the controller manufacturer if needed. More reliable customer service is required to address control system issues, answer occupant questions, and resolve problems like boiler failure—which should be inspected and repaired in a timely manner.

For many occupants, heat pumps and the integrated control of two systems are new technologies, and very different from boilers and radiators. Conducting a thorough training with the homeowners will save time and effort by avoiding return calls later. Controller manufacturers should also hold training sessions for the installers so that they can complete the initial setup and configure the control settings correctly. Upon completion of the installation, contractors should walk residents through the controls, showing the various operation modes for all zones. A tutorial for proper heating usage should counsel residents to minimize thermostat adjustments and large setbacks. Control manufacturers should consider offering a service plan for maintenance tasks and call back seasonally to schedule service.

5 References

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Appendix A. Customer Survey

All questions are required to be answered unless specified otherwise.

Q1. Overall, how satisfied or dissatisfied are you with your air-source heat pump system?

(multiple-choice, single answer permitted)

a. Very satisfied
b. Somewhat satisfied
c. Neither satisfied nor dissatisfied
d. Somewhat dissatisfied
e. Very dissatisfied

Q2. Overall, how satisfied or dissatisfied are you with your central heating system?

(multiple-choice, single answer permitted)

a. Very satisfied
b. Somewhat satisfied
c. Neither satisfied nor dissatisfied
d. Somewhat dissatisfied
e. Very dissatisfied

Q3. Overall, how satisfied or dissatisfied are you with your integrated control system?

(multiple-choice, single answer permitted)

a. Very satisfied
b. Somewhat satisfied
c. Neither satisfied nor dissatisfied
d. Somewhat dissatisfied
e. Very dissatisfied

Q4. How do you feel the temperature was in your home during the winter after the retrofit?

(multiple-choice, single answer permitted)

a. Too warm
b. Slightly too warm
c. Just right
d. Slightly too cold
e. Too cold

Q5. How do you feel the temperature was in your home during the summer after the heat pump installation?

(multiple-choice, single answer permitted)

a. Too warm
b. Slightly too warm
c. Just right
d. Slightly too cold
e. Too cold

Q6. How do you feel about the cost of heating energy from the air-source heat pump system?

(multiple-choice, single answer permitted)

a. Very high
b. Slightly too high
c. About right
d. Slightly too low
e. Too low

Q7. How do you feel about the cost of heating energy from the central heating system?

(multiple-choice, single answer permitted)

a. Very high
b. Slightly too high
c. About right
d. Slightly too low
e. Too low

Q8. How did your heating energy bills over the winter after the retrofit compare to what you expected prior to the retrofit?

(multiple-choice, single answer permitted)

a. Much higher than expected
b. Higher than expected
c. As expected
d. Lower than expected
e. Much lower than expected

Q9. Overall, how do you feel your new heating system performed over the winter after the retrofit compared to your previous heating system?

(multiple-choice, single answer permitted)

a. Much better
b. Slightly better
c. Around the same
d. Slightly worse
e. Much worse

Q10. How do you feel about the cost of cooling energy from the air-source heat pump system?

(multiple-choice, single answer permitted)

a. Very high
b. Slightly too high
c. About right
d. Slightly too low
e. Too low

Q11. How do you feel about maintenance of your heating system and control equipment compared to your old heating and cooling equipment?

(multiple-choice, single answer permitted)

a. Much easier
b. Slightly easier
c. About the same
d. Slightly more difficult
e. Much more difficult

Q12. Describe any aesthetic benefits or issues that you have experienced with the air-source heat pump system, central heat system and the integrated control, if any.

(open ended text box, not required)

Q13. Describe any unexpected benefits that you have gained from the air-source heat pump system, central heat system and the integrated control, if any.

(open ended text box, not required)

Q14. Describe any unexpected problems that you have experienced with the air-source heat pump system, central heat system and the integrated control, if any.

(open ended text box, not required)

Q15. Describe how you set your heating system. For example, heating setpoint of the heat pump, heating setpoint of the boiler/furnace.

(open ended text box, not required)

Q16. Describe your understanding of the purpose of the integrated control.

(open ended text box, not required)

Q17. Did you make adjustment to the integrated control? How?

(open ended text box, not required)

Q18. Have there been any other changes since the retrofit that may have impacted your energy use? Please give details. For example, changes in the number of people residing in the household and when this change occurred, the use of a thermostat setback/setup, or any other control changes.

(open ended text box, not required)

Q19. If you have any other comments about the survey and/or about your air-source heat pump system, central heat system and the integrated control, please enter them here.

(open ended text box, not required)

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