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An Integrated Control Method for Supplemental Minisplit Heat Pumps in Existing Homes

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An Integrated Control Method for Supplemental Minisplit Heat Pumps in Existing Homes

Prepared for:
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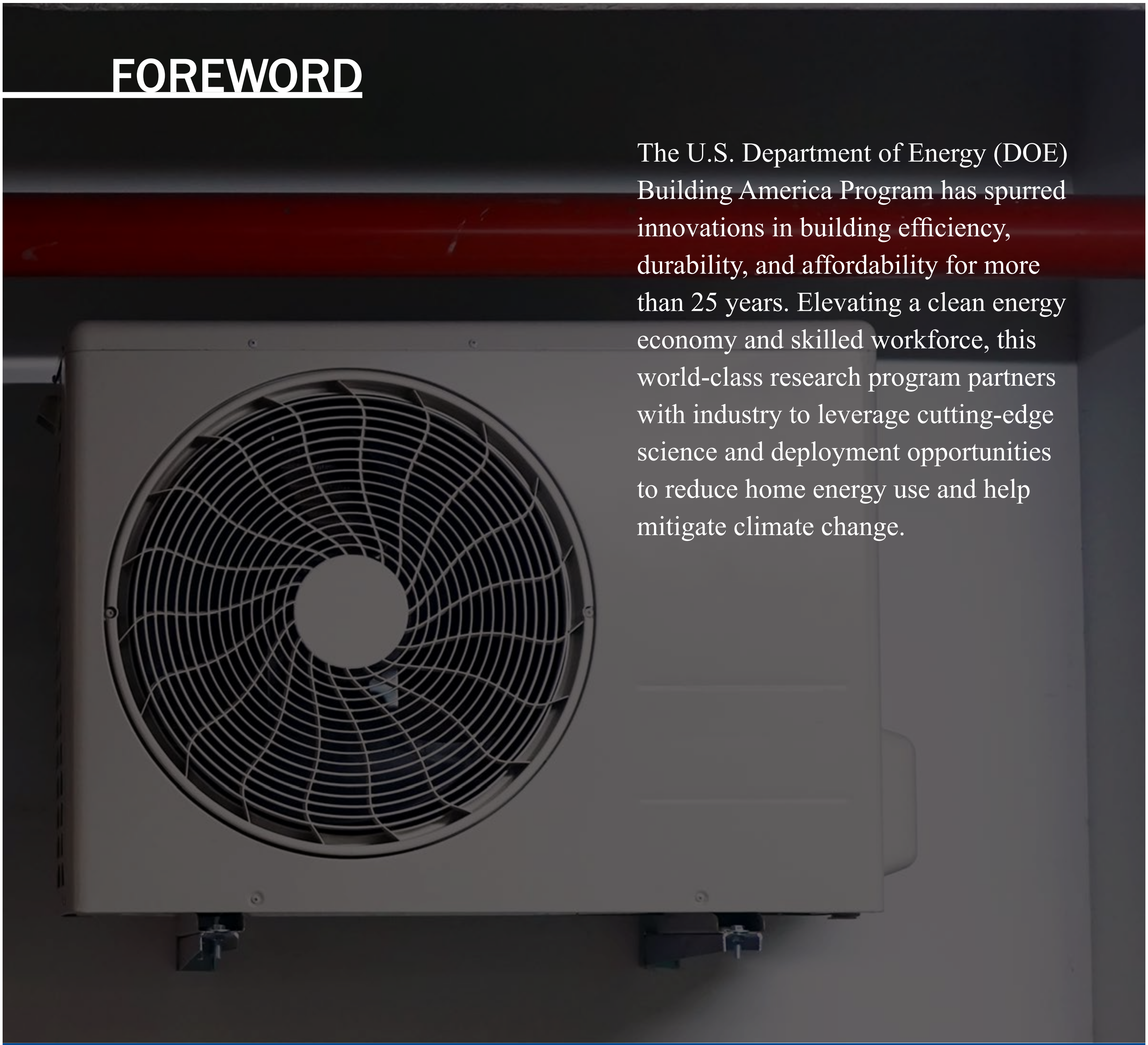
This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number EE0008183.

The work presented in this EERE Building America report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

FOREWORD

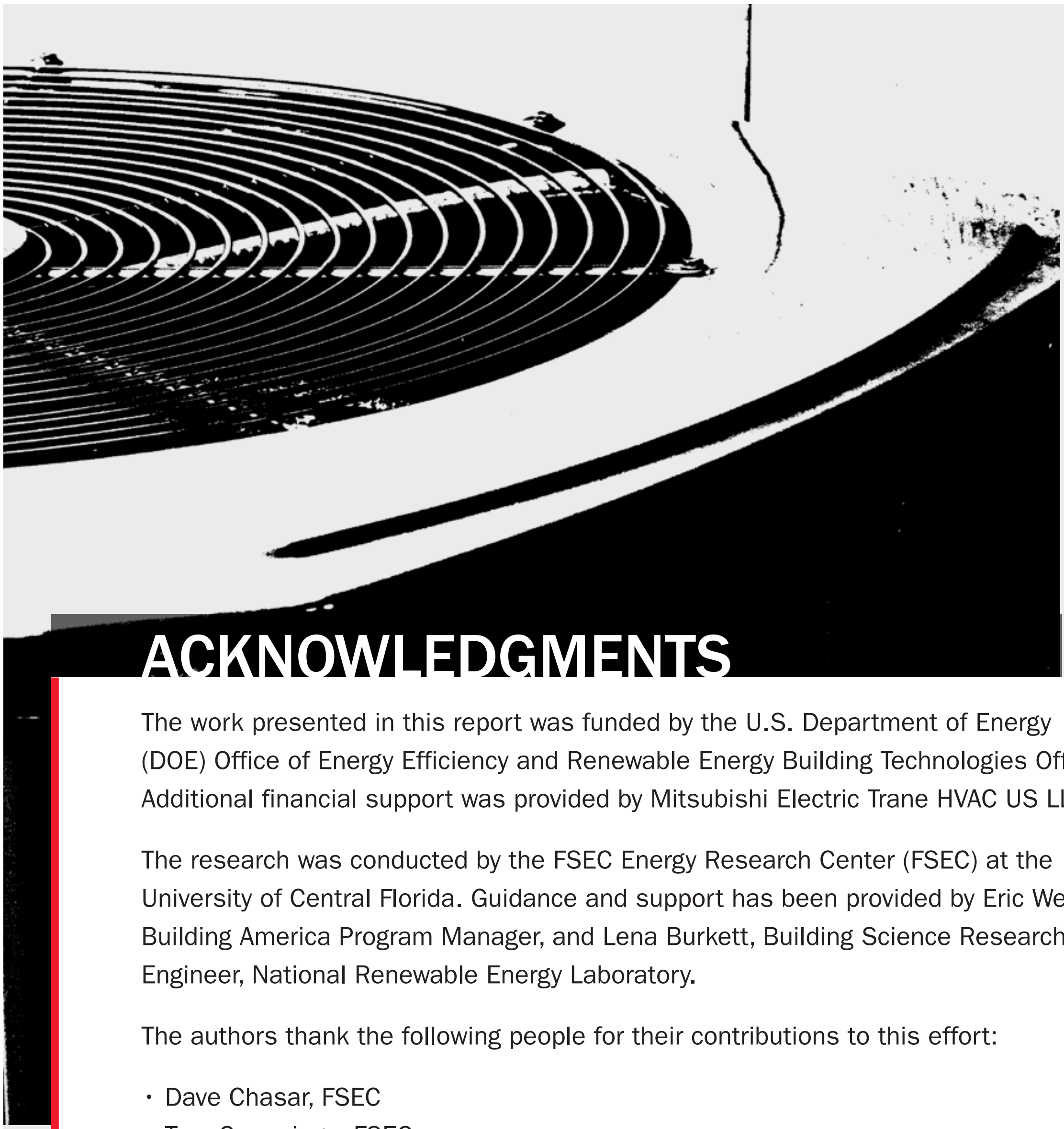


The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the FSEC Energy Research Center is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, *An Integrated Control Method for Supplemental Minisplit Heat Pumps in Existing Homes*, explores benefits of an advanced control strategy that manages interactions among a centrally located minisplit heat pump operating in conjunction with a home's central space-conditioning system.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.



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LIST OF ACRONYMS

ACCA Manual RS	Air Conditioning Contractors Of America Technical Manual Residential Systems Overview
API	application programming interface
CSCS	central space-conditioning system
FSEC	FSEC Energy Research Center
HSPF	heating seasonal performance factor
HVAC	heating, ventilating, and air conditioning
MSHP	minisplit heat pump
PDR	Phased Deep Retrofit
RH	relative humidity
SEER	Seasonal Energy Efficiency Ratio
TMY3	Typical Meteorological Year 3

EXECUTIVE SUMMARY

The FSEC Energy Research Center (FSEC) at the University of Central Florida has investigated low-cost space-conditioning upgrade solutions for existing homes since 2014. The retrofits involve installing a modest-capacity, centrally located, high-efficiency, ductless, minisplit heat pump (MSHP) for use in conjunction with the home's existing central space-conditioning system (CSCS).

This type of retrofit targets homes with older but not obsolete CSCSs that have not reached end of life, and presents a more cost-effective option to achieve space-conditioning energy savings than outright CSCS replacement. Energy savings are achieved by using the high-efficiency MSHP to offset runtime of the lower-efficiency CSCS, which also achieves reductions in associated duct losses and duct-leakage-induced infiltration.

During an earlier study, a 1-ton, 25.5-SEER, 12 heating seasonal performance factor (HSPF), inverter-driven MSHP was installed in the living room of 10 homes as a supplement to the existing CSCS. The MSHP was installed as close to the CSCS return as aesthetically acceptable to the homeowner, while accommodating manufacturer and installation contractor installation guidelines. Guidance provided to the occupants for "manual operation" of the independent systems was to set the MSHP thermostat 2°–4°F lower than the CSCS for cooling and to set it higher by the same amount for heating (often referred to as "droop"), but ultimately, occupants were allowed to operate the systems as they saw fit. This manual operation of the two independent space-conditioning systems (MSHP and CSCS) by the occupants demonstrated very promising heating and cooling energy savings and other associated benefits. Documented median energy savings were 33% (2,007 kWh/year) for cooling and 59% (390 kWh/year) for heating, with large variations depending on the central system heating equipment (savings for homes with electric resistance were much greater than those with a heat pump) (Sutherland 2016). However, unintended interactions occurring between the two non-integrated thermostats located in the same zone resulted in unpredictable system operation, limiting the potential for the occupants to easily optimize operation and achieve maximum benefits.

Leveraging the field homes and research of this earlier study, FSEC launched a new study funded by the U.S. Department of Energy to investigate the energy savings potential, given adherence to comfort management, if the control of the MSHP and CSCS were integrated. To investigate important control parameters and desired outcomes, system operation and thermal distribution data from homes that were retrofitted with a supplemental MSHP in the previous study were reviewed and analyzed. This review unveiled opportunities for cooling energy savings of this two-system configuration in three specific areas:

1. Prevalent repeated patterns of the MSHP cycling down shortly after the CSCS began to run.
2. When the MSHP was running, it was often performing a fraction of its maximum capacity.
3. Some occupants turned the MSHP off at night.

It was determined that some of the non-optimized MSHP operation resulted from occupants seeking to control comfort throughout all rooms of the home. Researchers concluded that an integrated control could achieve additional energy savings if it could cause the MSHP to operate more consistently and at higher capacity.

Integrated Control Design and Evaluation

The approach to optimize and integrate the independent MSHP and CSCS systems involved leveraging the internet connectivity of smart thermostats and their open application programming interfaces (API) to automatically control the MSHP set point in an optimized fashion. A cloud-based algorithm was developed that ran on a web server at FSEC that was capable of reading and writing information to/from the CSCS and MSHP thermostats. The controller hardware deployed included a Nest Generation 3 smart thermostat with the capability of remote temperature sensing via a separate wireless sensor to control the central system, and a Sensibo wireless smart thermostat to control the MSHP similar to the infrared signal on the MSHP remote control. The Nest remote temperature sensor allowed set points to be accommodated in different rooms (chiefly a bedroom) rather than only where the thermostat is positioned. A schematic of the hardware components is shown in **Figure ES-1**.

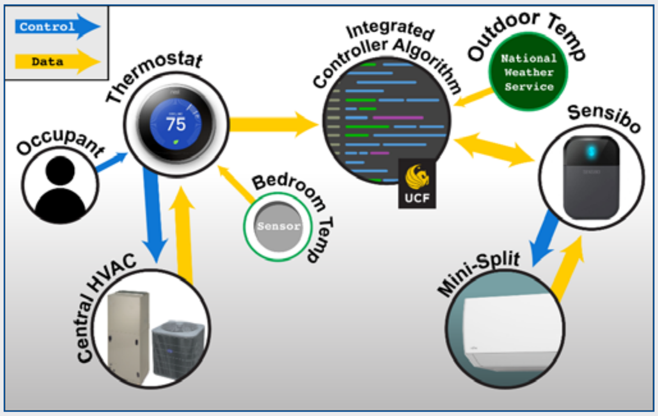

Figure ES-1. Integrated controller design

The control approach involves the occupant adjusting their CSCS thermostat as usual, including the use of a programmable schedule if desired. Occupants enter their desired set point, and any desired setups/setbacks. FSEC configured the Nest to read space temperature from its location in the main living space during the day and from the remote sensor in the bedroom during a nighttime block to ensure sleep time comfort needs. On a 15-minute time step, the program reads the CSCS mode (heat/cool/auto), set point, and room temperature (living room or bedroom) via the Nest API and feeds it to the algorithm along with additional inputs, including time of day and outdoor temperature read from a National Weather Service station. The algorithm calculates a set point instruction for the MSHP, which is written to the Sensibo smart thermostat controlling the MSHP. The algorithm also maintains the MSHP fan in "auto" via the Sensibo. Although occupants can manually adjust MSHP settings, the algorithm regains control at the start of the next 15-minute time step. If the occupant is unsatisfied with the MSHP operation, they are always able to override outside control of the MSHP by disconnecting the Sensibo to stop the connection.

Upon retrieval of the algorithm input data from the National Weather Service and both the Nest and Sensibo connected thermostats via API, the algorithm dynamically calculates the MSHP set point instruction as follows:

MSHP set point = CSCS_SP - (SO + AO) + NO, where

CSCS_SP = Central system set point, as set by occupant

SO = Standard offset, which is a static input value

AO = Additional offset, which varies with outdoor temperature and is defined as OT - CSCS_SP/TR

OT = Outdoor temperature

TR = Temperature response, which is a static input value

NO = Night offset, which is a binary (on or off) static input value.

In general, the algorithm seeks to dynamically adjust the MSHP set point below that of the CSCS for cooling ("dynamic droop") to ensure the MSHP use is maximized in order to minimize CSCS operation before the point of discomfort. To arrive at values for the static inputs described above, a simulation was built to iteratively tune the controller algorithm in response to local TMY3 weather data.

Integrated control was launched in four field homes in May 2019 and evaluated through October for cooling season performance. In two of the integrated controller sites, the MSHP was installed in 2014, which provided ample baseline data during the "manual operation" of the supplemental MSHP. Results for these sites are representative of a whole cooling season. The other two sites, however, had MSHPs installed in the second half of the 2018 cooling season. These sites were lacking 2018 baseline data as owners became accustomed to using both systems in concert over the proceeding several weeks. For these sites, a two-week "flip" period was invoked during the 2019 integrated controller experiments to collect additional baseline data. Results for these sites represent daily energy use differences at an average outdoor temperature of 80°F—an average daily outdoor temperature during Florida's cooling season. Regardless of the baseline period length, the energy savings projection method involved developing a linear regression model for each site, using average daily outdoor temperature to predict total daily heating, ventilating, and air-conditioning (HVAC) energy.

Algorithm inputs were refined based on collected data to improve the algorithm—both in terms of temperature control and energy savings. Some improvements were wholesale (applying to all sites), and others were applied to individual sites to address specific concerns or opportunities.

The shift of increasing MSHP use and reducing CSCS use is how the integrated controller scheme saves energy. This shift impacts thermal distribution throughout the house. One issue encountered at a few homes was that the living room temperature was excessively overcooled (relative to manual operation) during the early morning hours as the integrated systems worked to efficiently satisfy the bedroom set point during the night. At the sole two-story home, which has bedrooms on the second floor, high bedroom temperatures were experienced during the day while the controller scheme was operating off of the Nest's first floor sensor. These issues were corrected through algorithm refinement.

The cooling energy savings generated by the integrated controller, beyond savings achieved from the addition of the MSHP, were as high as 16%. These represent the results of a refined algorithm developed for each site as researchers adjusted the design at each site to maximize MSHP energy and address any comfort concerns, as described above. Savings indicate a change in cooling energy using the integrated controller over a baseline of supplemental MSHP being operated manually by the occupant. Results from the refined regression models and savings results are provided in **Table ES-1**.

ID	Manual Operation (CSCS+ MSHP)		Integrated Control		Savings	
	R^2	Seasonal Cooling Energy May–Oct (kWh)	R2	Seasonal Cooling Energy May–Oct (kWh)	Seasonal Cooling Energy (kWh)	%
7	0.61	4,670	0.60	4,120	634	11.8
8	0.56	3,467	0.47	3,052	415	12.0
	Adj. R^2	Daily Cooling Energy at 80°F (kWh)	Adj. R2	Daily Cooling Energy at 80°F (kWh)	Daily Cooling Energy (kWh)	%
13	0.54	17.7	0.81	20.4	(2.7)	(15.3)
14	0.71	12.8	0.73	10.7	2.1	16.4

Table ES-1. Cooling Energy Use Savings of Integrated Controller vs. Manual Operation of CSCS Plus MSHP

Annual cooling energy savings at Sites 7 and 8—11.8% and 12.0%, respectively—are the results of the more robust modeling based on longer-term data. Savings at Sites 13 and 14 are limited in that they compare two weeks of an imposed manual operation to two weeks of the integrated control. These short periods do not allow for a full cooling season energy use projection. The energy use results from these two sites are vastly different, with one showing negative cooling savings at 80°F of -15.3% (Site 13) and the other positive 16.4% (Site 14). The negative savings at Site 13 were not surprising because the homeowner was very involved in trying to minimize his central system energy use during the "flip" period under his control (manual operation). Further, during the integrated control period, better bedroom temperature control was achieved.

The MSHP and CSCS energy profiles for mid-summer days under manual operation (**Figure ES-2**) and integrated control (**Figure ES-3**) are below. MSHP energy is in green, CSCS is in red, and they are divided by 10 for easier review. Living room and master bedroom temperatures are also displayed, in purple and blue, respectively. **Figure ES-2** shows that under manual operation, a lot of CSCS energy is used during the day, and CSCS events trigger the MSHP to reduce power or even shut off—a typical pattern of the independently controlled systems described earlier. Conversely, **Figure ES-3** demonstrates that under integrated control, the ductless MSHP can carry the load from 12 a.m. until midafternoon. The living room temperature drops a little colder over the course of the sleeping hours and keeps the home even a little cooler during the day in this comparison. The master bedroom temperature is maintained at similar temperatures during sleeping hours under both scenarios, but is allowed to ride a little higher during the unoccupied daytime period under integrated control.

Data from the MSHP were normalized and analyzed to see if runtime increased with the integrated controller as desired. As MSHPs are able to vary their capacity, looking at a simple runtime fraction is not as useful as with fixed capacity equipment, especially because the MSHPs in this study were not instrumented to collect data on delivered capacity. To evaluate how the runtime changed with the introduction of our integrated controller, equivalent

Figure ES-2. MSHP and CSCS energy profile under manual control: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

Figure ES-3. MSHP and CSCS energy profile under integrated control: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue) full-load hours of both the CSCS and MSHP were evaluated for 12 sites, for all years available. Analyzing equivalent full-load hours normalizes the MSHP runtime with respect to full capacity, and is a more useful metric. To calculate equivalent full-load hours, an entire cooling season was reviewed to find the maximum power a system consumed for 1 minute. Then for every hour, the monitored energy for a given system was divided by the 98th percentile of power measured for a given minute during the full cooling season review, as described in fuller detail in Section 5.3.2. This was conducted for years before the MSHP was installed with the CSCS operating alone, years with the CSCS and MSHP installed but unintegrated, and the year of CSCS and the integrated control of the MSHP. The results are provided in **Table ES-2** and show not only a large reduction in the average CSCS equivalent full-load hours with the integrated controller, but a stark increase in average MSHP equivalent full-load hours as well.

Equivalent Full Load Hours (energy/max power 98th percentile; n=site years)	Average	Min	Max
CSCS			
Pre MSHP (n=16)	32%	24%	42%
Post MSHP, no control (n=25)	32%	15%	53%
Post MSHP, with control (n=4)	18%	14%	26%
MSHP			
No control (n=25)	13%	1%	42%
With control (n=4)	41%	30%	50%

Table ES-2. Equivalent Full-Load Hours for Multiple Sites

Because the home's thermal distribution is addressed differently under the integrated controller scheme, resulting in intentional zoning, a pre- to post-controller temperature distribution summary comparison is not instructive. Most important is that the occupants were always in control of their comfort; they could alter the set point on their Nest, they could disconnect the Sensibo to control the MSHP manually, and they could (and did) provide researchers feedback to help modify the algorithm settings specifically for their needs. Regarding relative humidity (RH), the integrated controller tended to keep levels lower than the manual operation of the CSCS and MSHP, averaging nearly 5% lower at two sites.

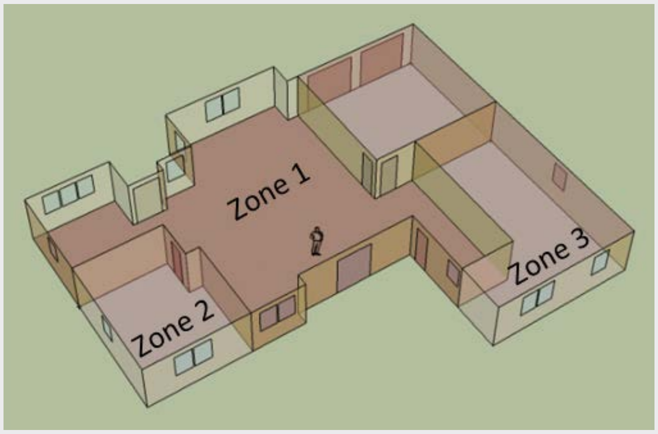

Figure ES-4. EnergyPlus Version 9.2 multizone model building sketch

The integrated controller experiments provided several lessons detailed in this report. Key takeaways are that overworking supplemental MSHP can erode savings, and that a market-ready solution will require flexibility for either occupants or contractors to alter inputs on setup.

End-of-Life Simulations

To investigate options for replacing the CSCS at end of life when the MSHP still has existing life, researchers created a multizone residential model using EnergyPlus™ Version 9.2, the U.S. Department of Energy's (DOE's) whole-building energy performance simulation program. **Figure ES-4** shows the multizone sketch-up. Simulations were conducted under a variety of replacement scenarios, including abandonment of the central system for a wholly ducted solution. The various configurations investigated are summarized in **Table ES-3**.

The modeling results suggest that space-cooling energy use is reduced by only 4% (for an estimated

Configuration Name	MSHP Systems	CSCS Systems
Baseline	None	Single-speed air-source heat pump, 3-ton capacity, 14.0 SEER, and 8.5 HSPF
Configuration 1	Single head variable-speed, 1-ton capacity, 23.0 SEER, and 12.5 HSPF	Single-speed air-source heat pump, 3-ton capacity, 14.0 SEER, and 8.5 HSPF
Configuration 2		Two-speed air-source heat pump, 3-ton capacity, 16.0 SEER, and 9.0 HSPF
Configuration 3		Variable-speed air-source heat pump, 3-ton capacity, 18.0 SEER, and 9.5 HSPF
Configuration 4	Single head variable-speed, 1.5-ton capacity, 23.0 SEER, 12.5 HSPF; Three head variable-speed minisplit air-source heat pump, 1.5-ton (2 heads of 0.75 ton) capacity, 18.5 SEER, and 9.5 HSPF	None

Table ES-3. Baseline and Advanced HVAC Equipment Test Cases Specifications

$15 annual savings) with a transition from a 14 SEER single-speed CSCS to the 16 SEER two-speed CSCS, and only 8% (for an estimated $31 annual savings) if choosing the more efficient 18 SEER variable-speed CSCS. Neither of these options makes sense based on cost-effectiveness given the premiums for either higher efficiency system. The all-ductless scenario is more promising, with results suggesting 25% annual cooling energy savings, or an estimated $101; however, costs would still outweigh the savings. Considerations such as enhanced zoning ability, room-by-room temperature customization, and added redundancy could be other reasons for choosing this end-of-life option.

Conclusions

This research involved integrating the control of a CSCS and a supplemental MSHP, and results demonstrate that a dynamic integrated controller solution that adjusts MSHP operation based on outdoor temperature and occupant schedules can improve cooling energy savings by as much as 16% beyond the energy savings achieved with the addition of the supplemental MSHP alone. Considering results obtained through past and current research, we expect that installation of a modest-capacity, centrally located, high-efficiency, ductless, MSHP together with an integrated controller can achieve cooling energy savings in the range of 12%–60%, depending on a number of factors including climate, system efficiencies and occupant comfort preferences. Although this research focused on cooling, the algorithm was designed to consider heating as well. Central Florida's mild weather during winter did not permit heating performance to be measured, but the algorithm was evaluated with simulation which showed that with similar algorithm inputs, it would also be able improve heating energy savings beyond the 59% achieved through installation of an uncontrolled MSHP and shown in the previous FSEC study.

The integrated controller algorithm and hardware components provided cooling energy savings by forcing the ductless high-efficiency MSHP to operate more while reducing runtime of the less-efficient ducted CSCS. The algorithm's energy savings success is attributed to specific areas of integration, including: slightly overcooling the main room in the early morning hours with the MSHP, which delayed the need for the CSCS engagement; minimizing or avoiding MSHP short cycling; and by introducing more MSHP runtime, including during sleeping hours, without jeopardizing bedroom comfort.

Important project lessons include:

- Special controller considerations should be given to two-story homes with bedrooms on the second floor to keep bedrooms from approaching uncomfortably high afternoon temperatures.

- A market-ready integrated controller solution can be offered with generalized algorithm input parameters, but should also include the flexibility to be customized (e.g., to avoid overcooling the main living area or a lack of cooling to a peripheral room, both of which occurred given specific behaviors and housing characteristics) to address the different needs of occupants and housing characteristics.

- Overworking supplemental MSHP can erode savings. Cooling temperatures set aggressively lower than the CSCS can force the MSHP to run near maximum output for extended periods, which can reduce performance enough to erode savings. Cooling energy savings from the integrated controller was found to be consistently larger (both in terms of kWh and percentage) at milder outdoor temperatures.
- CSCS fan cycling to improve whole-house temperature distribution with a supplemental MSHP cooling the main living area provides minimal benefit compared to the necessary energy expenditure for homes with ducts in unconditioned space.

Savings documented through experimentation in the occupied homes more than justify an anticipated added cost for a commercialized controller. Hardware costs for the controller used in these experiments was approximately $400, which could result in a simple payback of 5 years given 16% seasonal cooling energy savings vs. manual control. Discussion of simple payback for the addition of the MSHP itself is described in Section 1.3 of the report, and is expected to improve as markets mature and more incentives become available. However, it is important not to discount some intangible benefits of the supplemental MSHP approach: (1) The benefit of system redundancy if the CSCS fails due to need for repair or replacement. The MSHP can continue to provide some level of comfort extending the amount of time the occupants have to make a reasonable choice for CSCS repair or replacement. (2) The ability of an intelligently controlled system to provide demand response benefits to a utility by temporarily disabling the CSCS while the MSHP continues to provide comfort. Both of these benefits are demonstrated in Figure 25 in the conclusion section of the report. In this case, one of the sites from FSEC's original Phased Deep Retrofits (PDR) study lost use of their CSCS during summertime, but were comfortably able to get by until the system could be replaced.

The end-of-life simulations conducted to investigate the most cost-effective options for what to do when the CSCS expires suggest that as long as the ductless, more-efficient MSHP is able to address much of the building load (as seen in our field experiments), replacing the CSCS with the least-efficient model available is most cost-effective. A multiheaded ductless configuration could also be a consideration for such reasons as enhanced zoning ability, room-by-room temperature customization, and system redundancy, although cost-effectiveness alone would not be a reason to choose this option.

Similar field work in a heating-dominated climate is warranted given the promising results for cooling energy savings and the potential energy savings during a heating season suggested by simulation.

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1 Introduction

The FSEC Energy Research Center (FSEC), a research institute of the University of Central Florida, has investigated low-cost space-conditioning upgrade solutions for existing homes since 2014. The retrofits involve installing a modest-capacity, centrally located, high-efficiency, ductless, minisplit heat pump (MSHP) for use in conjunction with the home's existing central space-conditioning system (CSCS). This retrofit targets homes with older but not obsolete CSCSs that have not reached end of life, and presents a more cost-effective option to achieve space-conditioning energy savings than outright CSCS replacement. Energy savings are achieved by using the high-efficiency MSHP to offset runtime of the lower-efficiency CSCS, which also achieves reductions in associated duct losses and duct-leakage-induced infiltration.

Other benefits of the approach include the use of two redundant space-conditioning systems, each with the ability to maintain some level of comfort even in the event one unexpectedly stops working. Also, although not specifically investigated as part of this work, the innovation provides a cost-effective, "low-load ready" space-conditioning supplement (rather than replacement) to better manage energy use, risk, and comfort during the course of a progressive retrofit. Risks related to suboptimal latent control with oversized, single-stage equipment become critical when progressive home improvements drive space-conditioning loads lower, resulting in less system runtime, less indoor air mixing, and less moisture removal. Replacing conditioning equipment early in a deep retrofit, prior to the completion of envelope retrofits, runs the risk of installing equipment sized to meet the current load—equipment that will eventually be oversized—or conversely, installing undersized equipment in anticipation of planned improvements that will risk comfort issues in the near term. Integration of a variable capacity MSHP gives at least some ability to match capacity to load, both at the start and the end of a progressive deep energy retrofit.

Manual operation of the two independent space-conditioning systems (MSHP and CSCS) by the occupants has demonstrated heating and cooling energy savings and other associated benefits. However, unintended interactions between the two non-integrated thermostats located in the same zone result in unpredictable system operation, limiting potential for the occupants to easily optimize operation and achieve maximum benefits. In addition, a primary risk of maximizing runtime of a centrally located MSHP and minimizing runtime of a CSCS to achieve energy savings is that comfort in spaces off the main living area, such as bedrooms, can be reduced because of a reduction in air distribution. To overcome associated challenges with maximizing space-conditioning energy savings with a supplemental MSHP, FSEC developed a control scheme that integrates operation of the MSHP with the CSCS, and demonstrated the control in four occupied homes. The control considers the desired comfort parameters of the occupant and the space-conditioning load on the home, and automatically adjusts the MSHP to maximize energy savings.

Eventually, existing CSCS systems will reach the end of their life and require replacement. Capitalizing on the newer supplemental MSHP's ability to efficiently provide a portion of needed capacity, FSEC performed simulations to evaluate cost/performance tradeoffs of replacing the central system with additional MSHPs vs. a new CSCS. The simulations consider whether higher-efficiency CSCS systems may prove more cost-effective from a life cycle perspective, in the context of a supplemental MSHP providing a significant fraction of the space conditioning.

1.1 Scope and Objectives

The objective of the research was to demonstrate how integrated operation of the CSCS and the MSHP could result in additional space-conditioning energy savings, beyond what could be achieved without integration. Additional objectives included maintaining homeowner comfort and implementing a control interface that is easy to use. An overview of our objectives is depicted in Figure 1. Because few options for integrated controllers existed—and none that accommodated space-cooling operation—a control platform and algorithm needed to be created. To investigate important control parameters and desired outcomes, we reviewed and analyzed system operation and thermal distribution data from homes that were retrofitted with a supplemental MSHP in a previous study. Three additional homes were newly retrofitted with a supplemental MSHP and utilized for experimentation. Energy simulations were built, and an economic analysis was performed to evaluate options for when the existing central system reaches end of life.

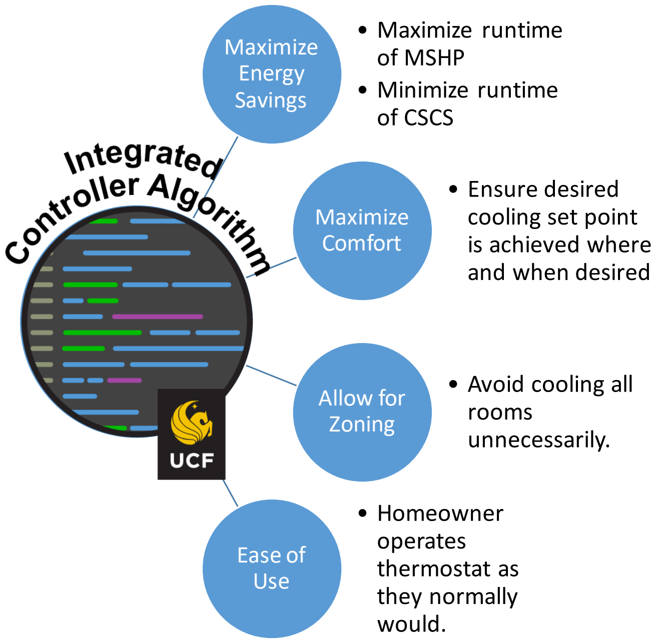

Figure 1. Integrated controller objectives

1.2 Research Questions

The research questions being explored are:

- What is the room-to-room thermal distribution pre- and post-installation of a supplemental MSHP?
- What is the effect of automated central system fan cycling on thermal distribution of conditioned air and energy savings of a supplemental MSHP design?
- What is the effect of an integrated control strategy that manages interactions between the central system and supplemental MSHP on thermal distribution and energy savings?
- In homes with a supplemental MSHP, what are the economics of choices for central system replacement?

1.3 Background

As part of FSEC's "Phased Deep Retrofits" (PDR) project, energy savings of a supplemental MSHP were initially documented in 10 central Florida homes. These 10 homes each received a 25.5 SEER, 12 HSPF, 1-ton, inverter-driven supplemental MSHP from August 2014–July 2015. Although referred to as "supplemental," the high-efficiency MSHP was set up to essentially act as the first line of defense for space conditioning by setting the thermostat lower than the central system for cooling, and higher than the central system for heating. The existing lower-efficiency central system was then engaged only if the minisplit could not maintain space comfort. Initially, the homeowners were advised to set the MSHP thermostat 2°–4°F lower than the CSCS for cooling, and higher than the central system by that same amount for heating (often referred to as "droop"), but ultimately they were allowed to operate the systems as they saw fit. The supplemental MSHP installations produced very promising results with median energy savings of 33% (6.7 kWh/day) for space cooling (with savings ranging from 21%–46% for nine homes and one home at 2%) and 59% (6.5 kWh/day) for heating (with savings ranging from 19%–82% for eight homes, one home at 9%, and one home with no pre-retrofit heating data), for a total annual space-conditioning energy savings of 34% (with savings ranging from 20%–50% for nine homes and one home at 4%). The average percent heating energy reductions were considerably greater for the six homes with electric resistance central heating, compared to the four homes with heat pumps. Large reductions to HVAC energy use during peak hours were also experienced—a 0.88 kW (28%) summer peak reduction and a 2.06 kW (56%) winter peak reduction. On average, main living room temperature and relative humidity (RH) varied little between pre- and post-MSHP installation, but a room-to-room evaluation was not conducted in the PDR study.

FSEC's PDR project also demonstrated that ductless supplemental MSHPs have great potential to reduce space-cooling energy in a hot-humid climate by reducing the runtime of inefficient existing central systems with leaky and heat-gain-prone duct systems. Research is limited on other southern-climate MSHP installations in existing homes where the primary focus is on cooling. Sparse data suggest that MSHPs are primarily installed in cooling-dominated climates to replace noisy window units or to serve a previously unconditioned space, rather than to displace less efficient central air-conditioning systems where MSHPs can also be useful (Faesy 2014). Reports from many Florida mechanical contractors support this, suggesting that MSHPs are primarily being installed into a master bedroom, a garage, or distant, poorly conditioned zones to condition space outside of the existing HVAC design, as a less expensive alternative to upgrading or expanding the existing central system (The NEWS 2015, 2016; Sutherland 2016 personal communication). When installed in a supplemental arrangement, contractors report concerns about an MSHP's ability to interact with the central system effectively and manage whole-house comfort. High installation prices partially resulting from this immature, low-demand market resulted in a simple payback of 14 years[1] for the supplemental MSHP in FSEC's PDR project, which shows that a combination of a maturing market as well as innovations such as advanced controllers to enhance savings and other benefits are required to achieve good market penetration in cooling-dominated climates.

With large reductions to peak demand, and the ability to foster transition to electric heating fuel for more renewable integration and price stabilization, utility incentives for an MSHP are attractive to utility companies and homeowners alike. Utilities in heating-dominated climates such as Green Mountain Power and regional efficiency programs such as those from New York State Energy Research and Development Authority (NYSERDA), MassSave, and Efficiency Maine have been incentivizing installation of high-efficiency heat pumps. However, impact evaluation studies show that the full potential of energy savings from installation of an MSHP is not achieved. A study in a heating-dominated climate of 152 homes retrofitted with MSHPs showed the ductless minisplit being used for only 51%–64% total potential operating hours due to a lack of proper control (Korn et al. 2016). This study suggested the development of integrated controls allowing the MSHP and CSCS to share information to increase energy savings of the two-system approach. Analysis of data from FSEC's PDR study resulted in similar findings for lost space-cooling energy savings, described in detail in Section 3.4.

Research leading to the development or demonstration of integrated controls is scarce. Pacific Northwest National Laboratory recently devised methods to test simple control functionality in simulated occupancy laboratory homes and used those results to build energy simulations. Simulated results show potential for between 30%–40% energy savings in most climates when an MSHP is installed with controls that enable complex scheduling of MSHP and CSCS systems (Chen 2020).

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[1] Intangible benefits, such as resiliency from an MSHP acting as a redundant system and comfort improvements, were not included in payback analysis.

2 Home Site Characteristics and Instrumentation

2.1 Home Characteristics

The field homes used in this project are almost exclusively single-story (Site 7 is the exception with two stories) and average about 1,900 ft^2 of living area. All were involved in and received the bulk of their instrumentation as part of FSEC's previous PDR study, with most receiving their MSHP as part of that study. The CSCS nominal efficiency ranges from 10 to 17 SEER and capacity from three to five tons. The homes were modeled in Energy Gauge USA v6.0.02 to generate ACCA Manual J load calculations, which indicated several CSCS were slightly oversized. General site characteristics for homes are provided in Table 1.

All sites are in east central Florida. To distinguish which homes are part of which evaluation aspect of the project, the sites are identified as original, manual optimization, or controller. Ten homes received a Panasonic XE12PKUA, SEER 25.5 Btu/Wh, 12-HSPF MSHP in 2014 or 2015 as a supplement to their existing central system as part of the above-referenced PDR study and are referred to in this report as "original" sites. Three of the original sites were selected for manual set point optimization experiments and are referred to as "manual optimization" sites. A fourth site (Site 15) was added mid-study to replace one of the manual optimization homes that exited the study mid-experiment. (This fourth manual optimization site is home to research staff and had received the same Panasonic equipment as a supplemental system in 2016.) There are four "controller" sites identified, which are the homes used for the integrated controller evaluation. This group consists of two homes from the "original" group to receive an MSHP under the previous study and two homes that received a supplemental MSHP as part of this study. One additional home (Site 10) also received a supplemental MSHP as part of this study but was not utilized for controller experiments due to a CSCS that was incompatible with the eventual controller design.

Table 1. Site and HVAC Characteristics

ID	Evaluation	Year Built	Number of Stories	Living Area (ft^2)	# of Occ	Year of AHU[a]	Year of Compressor	CSCS Size (tons)	Manual J Peak Load (tons)	CSCS SEER [b]	Heating Type	Duct Leakage (Qn,out)[c]
1	Original	1993	1	1,856	1	1993	2010	3.5	3.5	13	Heat Pump	0.05
2	Original	2006	1	2,328	2	2006	2006	5.0	4.5	13	Heat Pump	0.10
3	Original/Manual Optimization	1984	1	1,594	2	2000	2000	3.0	3.0	12	Heat Pump	0.63
4	Original/Manual Optimization	1982	1	2,231	3	2002	2014	4.0	3.0	13	Resistance	0.07
5	Original	1981	1	1,628	2	2013	2013	3.5	2.5	13	Resistance	0.12
6	Original	1980	1	1,946	3	2001	2002	3.5	3.0	14	Resistance	0.05
7	Original/Controller	1986	2	1,978	3	2010	2010	3.5	3.5	15	Resistance	0.09
8	Original/Manual Optimization/ Controller	1995	1	2,050	2	2008 Pkg. Unit		5.0	5.0	12	Resistance	0.05
9	Historic	1999	1	1,390	2	1999	1999	2.5	2.0	10	Heat Pump	0.03
10	Original	1987	1	1,520	3	2006	2006	3.0	2.0	15.5	Resistance	0.04
13	Controller	1988	1	2,554	4	2013	2013	5.0	4.5	16	Heat Pump	0.06
14	Controller	1981	1	1,559	4	2013	2013	3.0	2.5	17	Heat Pump	0.04
15[d]	Manual Optimization	1991	1	1,951	1,2	2008	2008	4.0	n/a	17	Resistance	n/a

[a] Air handling unit

[b] Some systems were apparently unmatched; stated are manufactuer listed compressor efficiencies.

[c] Duct leakage measured at a test pressure of negative 25 pascals (Pa) with respect to the outside, divided by the building's conditioned floor area.

[d] Site 15 is a substitute site added during this study to replace Site 3, which exited the study during the fan cycling experiments.

2.2 Instrumentation

Sample Intervals: Energy data were collected on a 1-minute time step, and temperature and RH data on a 15-minute time step. Energy data were retrieved daily from the internet via broadband connection. Temperature and RH data were manually retrieved from the sites every few months. Redundant temperature and RH devices were deployed in some homes to retrieve data daily from the internet via broadband connection at a 15-minute time step. Outdoor temperature and RH were obtained from nearby weather stations.

Sample Accuracy: National Weather Service measurements were used for outdoor temperature and RH and were obtained from the nearest available station, typically less than 20 miles away from the test homes. Although potentially less accurate than using monitored on-site weather, we envision that a commercial controller may obtain weather data from an internet source to avoid the associated sensor cost. The stated accuracy of the outdoor temperature measurements by the National Weather Service is ±1°F. Indoor temperatures were measured using Onset HOBO U-10-003 portable loggers with a stated accuracy of ±0.95°F for temperature and ±3.5% for RH up to 85%, and using the Point Six wireless transmitter with the Sensirion SHT71, with stated accuracy of ± 0.4°C (~0.72°F), at 25°C (~77°F), and ±3% RH (from 20%–80%). Each site had four to eight 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 the bedrooms and main living area of the manual optimization and controller homes.

Energy use was measured by SiteSage loggers (formerly eMonitor), generally using 50-amp current transformers. These have a stated accuracy of ±1% between 10% and 130% of their rated output. The relative error becomes an artifact of the load itself. For a 3,000-watt (W) compressor at a given point, this would result in approximately ±30 W in measurement uncertainty for evaluating absolute measurements (kilowatt-hours [kWh] for one site compared to another). For retrofit measurements (before/after), the measurement equipment-related variation is much lower, such that measurements should be ±0.5% or better. For example, if the air conditioning in a home was using 25 kWh/day, the average load would be 1,042 W with an absolute uncertainty of 0.5 kWh/day. If the estimate was between pre- and post-retrofit periods (the situation in this evaluation), the uncertainty would be 0.12 kWh/day, although this can be computed for individual cases if the results are in doubt. A summary of the monitoring instruments used for this project is provided in Table 2.

Table 2. Monitoring Equipment and Accuracy

Measurement	Equipment	Accuracy
MSHP energy, CSCS, and general data acquisition	Sitesage Energy Monitor with Current Transformers	±1% of rated current
Indoor temperature and RH: analysis purposes	Onset HOBO UX100-001A, UX100-011	±0.21°C, 2.5% RH of rated current
Indoor temperature and RH: real time monitoring, redundancy	Pointsix 3008-04-V6 Wi-Fi transmitter	±0.41°C, 3% RH

3 Additional Evaluation of Supplemental MSHP Installations with Standard, Non-Integrated Operation

3.1 Cooling Energy Savings Persistence of Original Sites

An evaluation investigating the cooling energy savings' persistence was conducted at three original sites that had previously received a supplemental MSHP to see if savings documented as part of FSEC's PDR project persisted in subsequent years. The energy use savings were predicted using a linear regression model using average daily outdoor temperature to predict cooling energy use, and results are provided in Table 3. Savings were normalized using TMY3 weather data, and normalized savings were 24% three years after the MSHP installation for Site 4, 41% three years out for Site 8, and 34% two years out for Site 15.

Table 3. Annual Cooling Energy Savings After Receiving Supplemental MSHP

Supplemental MSHP Cooling Energy Savings	Post Year 1	Post Year 2	Post Year 3
Site 4	30%	23%	24%
Site 8	38%	51%	41%
Site 15	28%	34%	N/A

3.2 Cooling Energy Savings of New MSHP Sites

The three sites that received MSHPs as part of this current study were evaluated for cooling energy savings to see if baselines would be similar to FSEC's past PDR study. The evaluation was fairly limited because the occupants had received their MSHP toward the end of the cooling season, which did not necessarily allow time for them to adjust to manual methods of controlling the independent systems serving the same zone. Still, a short-term analysis was conducted comparing periods of similar weather before and after the MSHP was installed. Cooling energy savings were estimated to be 14%, 34%, and 39%. The 14% and 39% energy savings resulted from a one month pre- and one month post-evaluation period, and obtained from regression results using the average daily temperature for that evaluation period.[2] The third site (Site 13, with 34% estimated savings) began to incorporate elements of our advanced controller almost immediately upon installation of the minisplit. Given the lack data with the minisplit without advanced control, we compared three sets of similar pre/post weather days, which produced 32%, 34%, and 39% energy savings. We are reporting the median of these. Site 13 was

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[2] The average outdoor temperature for the short evaluation period (83°F) was warmer than the average for the cooling season (80°F), and we caution extrapolation of these results to an entire cooling season. However, research on the 10 supplemental minisplit sites from the earlier study showed the difference between cooling energy savings run with an average outdoor temperature of 80°F vs. 83°F to be within 1% of each other.

particularly aggressive with use of their new supplemental system and reduced their CSCS cooling energy by 83% during a longer-term evaluation, though bedroom temperatures rose above the home's main body temperatures during sleeping hours.

3.3 Analysis of Historical Multiroom Temperature/Relative Humidity Data and Homeowner Interviews

In order to determine baseline comfort metrics that an integrated controller would need to achieve, historical temperature and RH data from the original sites were analyzed pre- and post-installation of a supplemental MSHP. An important design element of the integrated controller is that it maintains or improves comfort compared to a non-integrated situation with manual control.

The initial point of interest was how the addition of a non-integrated MSHP impacted comfort. As only data from July and August were available prior to installation of the supplemental MSHP, data from the following July and August were analyzed for the post-MSHP condition. As seen in Table 4, the results include the average and maximum values, as well as the percentage of time the Delta T between bedroom and living room exceeded 3°F, per ACCA Manual RS guidelines. Only RH measured in the living room is shown because room-to-room deviations tend to be smaller than with temperature, which is often based on external load factors. Excursions from ACCA Manual RS guidelines are almost nonexistent in both the pre- and post-MSHP condition, except in one bedroom in Site 8. While it appears that the addition of the MSHP improved this site's temperature distribution, this likely resulted from other occupant-induced factors. The fact that comfort—evaluated as temperature difference from room to room—changed very little when the MSHP was added makes sense. As noted in Section 1, homeowners manually operate their non-integrated systems to achieve comfort first, and energy savings second. Maximizing energy savings is limited by the interactions between the MSHP and CSCS previously discussed, and this analysis shows that homeowners are unlikely to sacrifice comfort for maximum energy savings.

Table 4. Hourly Temperature and RH, and Room-to-Room Delta Temperatures Pre- and Post-MSHP Addition

	Pre-MSHP (July–Aug 2014)				Post MSHP (July–Aug 2015)			
	Average	Max	%>3°F DT	n	Average	Max	%>3°F DT	n
Site 3								
Living room RH (%)	52.9				54.9			
Living room T (°F)	76.5				77.3			
MBR Delta T (°F)	(1.1)	1.1	0.0%	1,493	(0.3)	1.5	0.0%	817
BR2 Delta T (°F)	(1.2)	2.5	0.0%	1,531	(1.0)	0.3	0.0%	816
BR3 Delta T (°F)	(1.7)	2.5	0.0%	1,531	Data not available			
Site 4								
Living room RH (%)	52.4				52.1			
Living room T (°F)	76.7				76.5			
MBR Delta T (°F)	0.5	2.0	0.0%	1,644	0.1	2.1	0.0%	1,614
BR2 Delta T (°F)	(1.1)	1.0	0.0%	1,644	(1.1)	1.5	0.0%	1,614
BR3 Delta T (°F)	(1.4)	0.2	0.0%	1,644	(1.1)	1.7	0.0%	1,614
Site 8								
Living room RH (%)	48.7				43.1			
Living room T (°F)	76.2				75.0			
MBR Delta T (°F)	(0.8)	1.0	0.0%	1,200	0.9	3.0	0.0%	1,594
BR2 Delta T (°F)	(0.9)	0.7	0.0%	1,200	0.3	2.4	0.0%	1,594
BR3 Delta T (°F)	2.2	4.9	14.9%	1,181	2.2	6.5	8.8%	1,594

It was important to also consider more recent data in order to baseline comfort metrics prior to implementation of a controller, as homeowner comfort preferences can change over time for various reasons, including occupancy changes. Focusing on comfort during the cooling season, we determined each site's cooling balance point—the lowest daily average ambient temperature for which cooling energy use occurred. For all cooling hours over the prior 12 months, the differences in hourly average temperature between the bedroom and the main living area (Delta T, calculated as bedroom minus living room) were plotted against the daily average outdoor temperature. For each home, this evaluation was conducted for each bedroom and for each of the following circumstances, with results provided in Table 5:

1. Hours with MSHP runtime, regardless of CSCS runtime
2. Hours with CSCS runtime, regardless of MSHP runtime
3. Hours with MSHP runtime, but no CSCS runtime OR hours with CSCS runtime, but no MSHP runtime.

The summary results in Table 5 include the average and maximum values, as well as the percentage of time that Delta T between bedroom and living room exceeded 3°F.

Table 5. Hourly Temperature and RH, and Room-to-Room Delta Ts for Different Mechanical System Configurations

Hours with:	MSHP Running				CSCS Running				CSCS but no MSHP[a]			
	Avg.	Max	%>3°F DT	n	Avg.	Max	%>3°F DT	n	Avg.	Max	%>3°F DT	n
Site 3												
Living room RH (%)	63.6				64.0				65.1			
Living room T (°F)	73.7				73.4				72.4			
MBR Delta T (°F)	(0.7)	1.6	0.0%	2,923	(0.7)	1.6	0.0%	3,950	(0.8)	1.4	0.0%	1,027
BR2 Delta T (°F)	(0.0)	4.0	0.8%	2,923	(0.1)	4.0	0.7%	3,950	(0.2)	3.3	0.2%	1,027
BR3 Delta T (°F)	(0.5)	1.9	0.0%	2,923	(0.4)	1.9	0.0%	3,950	(0.4)	1.2	0.0%	1,027
Site 4												
Living room RH (%)	57.2				55.4				55.4			
Living room T (°F)	76.6				74.8				73.0			
MBR Delta T (°F)	(0.1)	2.6	0.0%	2,232	0.6	3.0	0.0%	3,402	1.3	3.0	0.0%	1,779
BR2 Delta T (°F)	(1.8)	3.3	0.1%	2,232	(1.6)	3.6	0.1%	3,402	(1.0)	3.6	0.2%	1,779
BR3 Delta T (°F)	(1.7)	3.0	0.0%	2,232	(1.5)	4.6	0.2%	3,402	(0.9)	4.6	0.3%	1,779
Site 8												
									MSHP but no Central[a]			
Living room RH (%)	46.3				43.7				48.1			
Living room T (°F)	75.8				76.2				75.5			
MBR Delta T (°F)	1.0	4.0	0.6%	5,250	1.2	4.05	1.2%	2,199	0.8	3.5	0.1%	3,067
BR2 Delta T (°F)	0.3	2.8	0.0%	5,250	0.1	2.45	0.0%	2,199	0.4	2.8	0.0%	3,067
BR3 Delta T (°F)	1.8	4.6	3.0%	5,250	1.8	4.55	3.5%	2,199	1.8	3.7	2.60	3,067

[a] Limited events for either CSCS but no MSHP or MSHP but no CSCS. One or the other configuration is summarized.

In general, results from all sites and cases show no clear differences in room-to-room temperature among central-system-only runtime, central with MSHP runtime, or MSHP runtime alone. Also, rarely does the Delta T ever exceed the ACCA Manual RS guideline of 3°F, whether the supplemental MSHP was running or not. Also, the largest excursions, which are observed at

Site 4, occur when the central system is running. In two of the three sites, slight reductions to indoor RH are seen when the CSCS is running.

Figure 2 and Figure 3 present some of the results from the analysis at Site 3, where we compare the hourly bedroom-living room Delta T to the daily average outdoor temperature for hours with central system runtime but no MSHP runtime (left plot), and then for all hours when the MSHP was running regardless of central system power (right plot). The Y-axis is the room Delta T, the X-axis is the outdoor temperature, and each point represents average temperature for an hour, color coded by month. Positive numbers on the Y-axis indicate hours when the bedroom temperature was warmer than the living room. Figure 2 scatter plots are of the master bedroom-living room Delta Ts.

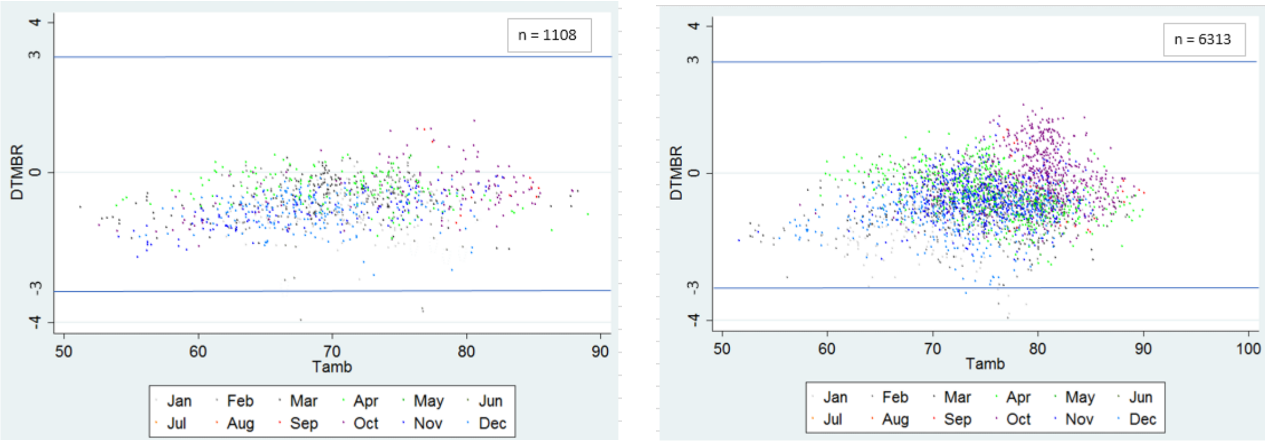

Figure 2. Site 3 master bedroom minus living room delta T (°F) against outdoor T (°F) for hours with CSCS runtime only (left) vs. hours with any MSHP runtime (right)

In the master bedroom, the cases of greatest excursion are in the cooler months, where the bedroom temperatures are actually cooler than the living area. During the warmest months (points reddish in color), bedroom temperatures are generally warmer than in the living area. While this is especially clear in the plot on the right (with MSHP runtime), the hourly Delta T is well below 3°F and rarely more than 1.5°F. Figure 3 scatter plots are of the second bedroom-living room Delta Ts.

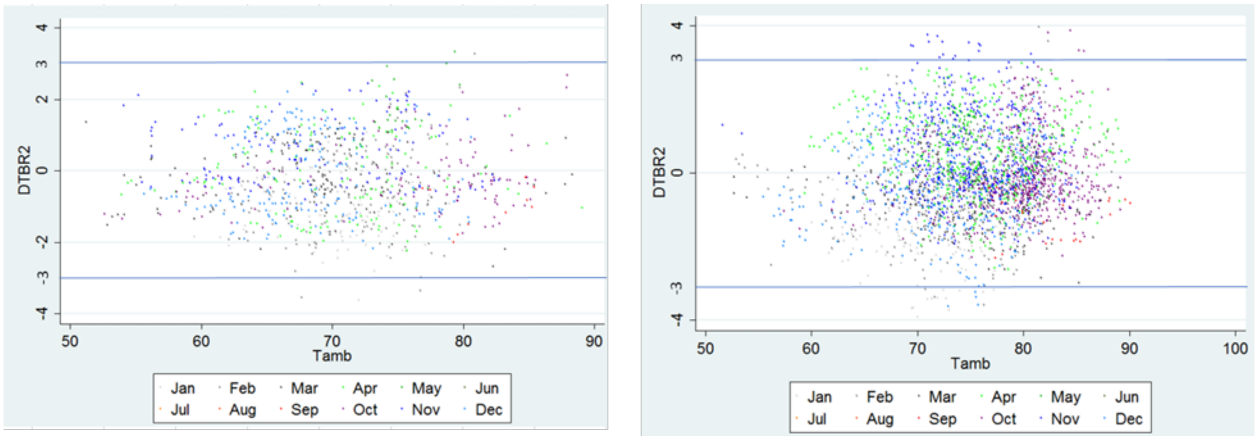

Figure 3. Site 3 second bedroom minus living room delta T (°F) against outdoor T (°F) for hours with CSCS runtime only (left) vs. hours with any MSHP runtime (right)

More excursions are observed in the second bedroom than the master bedroom, and during both central system-only hours and central system plus MSHP. Still, rarely does the temperature delta exceed 3°F. It is noteworthy that the second bedroom was unoccupied during some of this period.

These findings of minor temperature excursions between rooms based on monitored data analysis were also evident during homeowner interviews, except for Site 3 occupants, who reported that temperatures were too warm in the master bedroom in recent early mornings. However, we discovered that Site 3's central system programming was not set as the occupants thought it was. Other sites' occupants reported that if they did have discomfort in the master bedroom, they would adjust their central system set point down to achieve comfort.

3.4 Cooling Energy Savings Potential Missed

An initial element of our research was to investigate the energy use patterns of both systems in original sites from our prior research where the supplemental MSHP was manually operated by homeowners with only general set point recommendations, to see if and where opportunity for increased savings might exist. We discovered opportunities for cooling energy savings in three specific areas. An example of one common savings-eroding signature is provided in Figure 4. Here we see the MSHP (in green) cycling down shortly after the CSCS (in red with power divided by 10) begins to run. Also, the MSHP is only running at a fraction of its maximum output (~100 W versus ~900 W). This led us to believe additional energy savings could be achieved by forcing the MSHP to operate (1) more consistently and (2) at higher capacity. The goal would be to avoid as many CSCS cycles as possible.

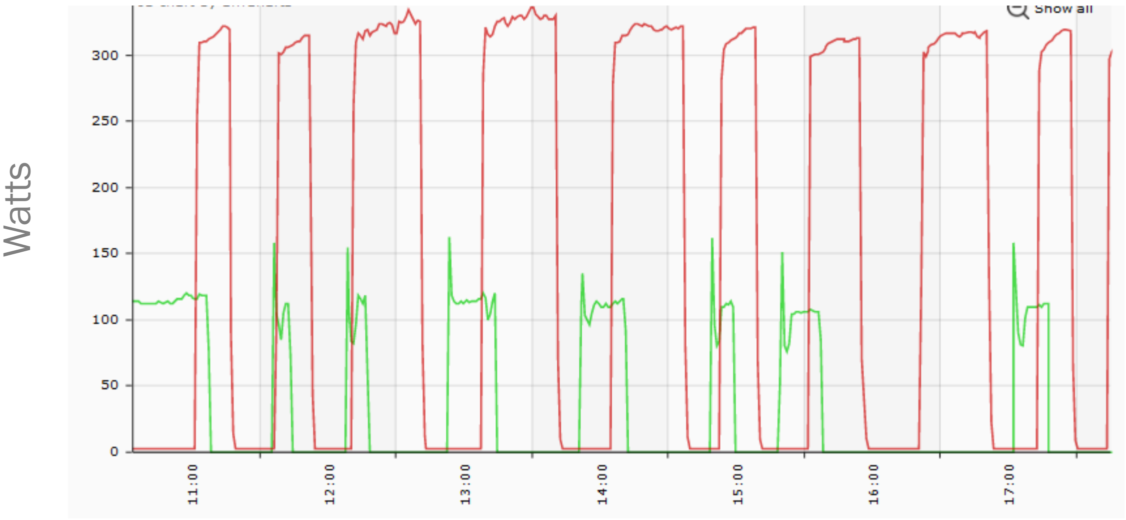

Figure 4. Demonstration of MSHP short cycling and limited capacity: CSCS power/10 (red), MSHP power (green)

Figure 5 demonstrates another way savings from the manually controlled supplemental MSHP may have been falling short of potential: some occupants were turning the MSHP off at night. Note that this site was turning their MSHP off between 10 p.m. and 8 a.m. The stated reason for this occupant behavior was to ensure CSCS runtime at night to achieve bedroom comfort. But we questioned: can we induce *some* MSHP energy overnight to reduced CSCS without jeopardizing comfort? And if so, how much?

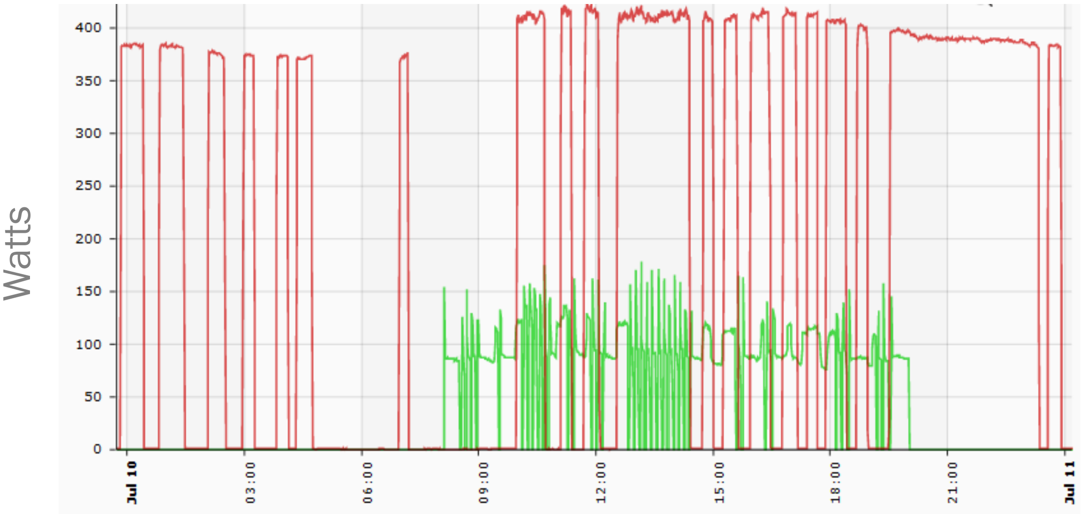

Figure 5. Demonstration of no MSHP nighttime operation: CSCS power/10 (red), MSHP power (green)

4 Controller Design Experiments

Prior to implementing an integrated controller, set point optimization experiments were conducted at three original MSHP sites to determine whether set point adjustment could be used as the basis for control. Unique schedules were devised for each site to optimize space-conditioning energy savings and maintain thermal comfort. We use Site 8 to highlight this process and results.

4.1 Site 8 Set Point Optimization Experiment

Before the set point optimization intervention at Site 8, the homeowner had his central system set to 74°F and his MSHP to 76°F, with no programmable schedule. This is a prime example of a non-optimized control setting. The MSHP ran considerably, and this site continued to show strong space-conditioning energy savings, but set points were not maintained as we originally instructed. To optimize savings and maintain comfort, the owner agreed to (1) adjust the MSHP to 74°F, (2) set the central system to 75°F during the day and 76°F during sleeping hours, and (3) cycle the central system fan for at least 15 minutes of every hour between 3 a.m. and 9 a.m. (this particular occupant's sleeping hours). Fan cycling was implemented during evening hours, when attic duct gains are lowest, to see if it could improve comfort in the bedroom. However, subsequent review of data indicated minor to negligible improvement to temperature such that the resulting benefit did not offset central system fan energy required. Outdoor conditions were variable post-intervention, so in this evaluation we only compare one day pre- (June 11, 2018) to one day post-intervention (June 15, 2018) when outdoor conditions were very similar. This site's single occupant is a retiree with a very regular schedule, so the results of this one-day comparison are deemed to be a reasonably accurate estimation of short-term seasonal energy savings. Table 6 provides the changes in cooling energy, living room temperature, ambient temperature, and outdoor dew point for these days. MSHP power nearly doubled, while the central system power was down by 8.0 kWh/day. Cooling energy use was reduced by 5.2 kWh/day (18%), and there was little change to the daily average living room temperature.

Table 6. Site 8 Set Point Optimization Cooling Savings and Temperature Changes

	MSHP (kWh/Day)	Central (kWh/Day)	Total HVAC (kWh/Day)	Living Room Temp (°F)	Ambient Temp (°F)	Ambient Dew Point (°F)
Pre-Intervention (June 11, 2018)	3.3	25.9	29.2	75.3	79.5	69.9
Post-Intervention (June 15, 2018)	6.2	17.8	24.0	75.4	81.1	72.2
Pre – Post	2.9	(8.0)	(5.2)	0.1	1.6	2.3
Energy Savings	-86%	31%	18%			

To investigate interaction between the central system and MSHP, and to evaluate changes in living room temperatures, we looked at daily trends for these days. Using 1-minute data, we compare pre-intervention (Figure 6) to post-intervention (Figure 7). The left Y-axis is watts, used for central system power (red) and MSHP power (green); the right Y-axis is temperature (°F) for tracking the living room (purple) and master bedroom temperature (light blue). Unfortunately, pre-intervention bedroom temperatures data were not available.

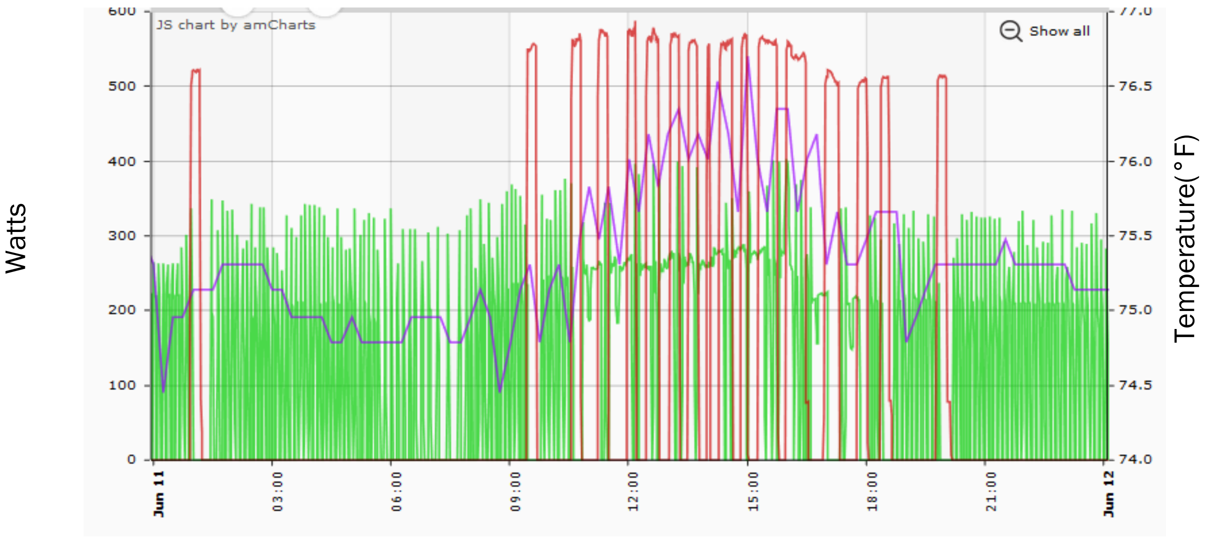

Figure 6. Site 8 pre-intervention cooling profile: CSCS power/10 (red), MSHP power (green), living room temperature (purple)

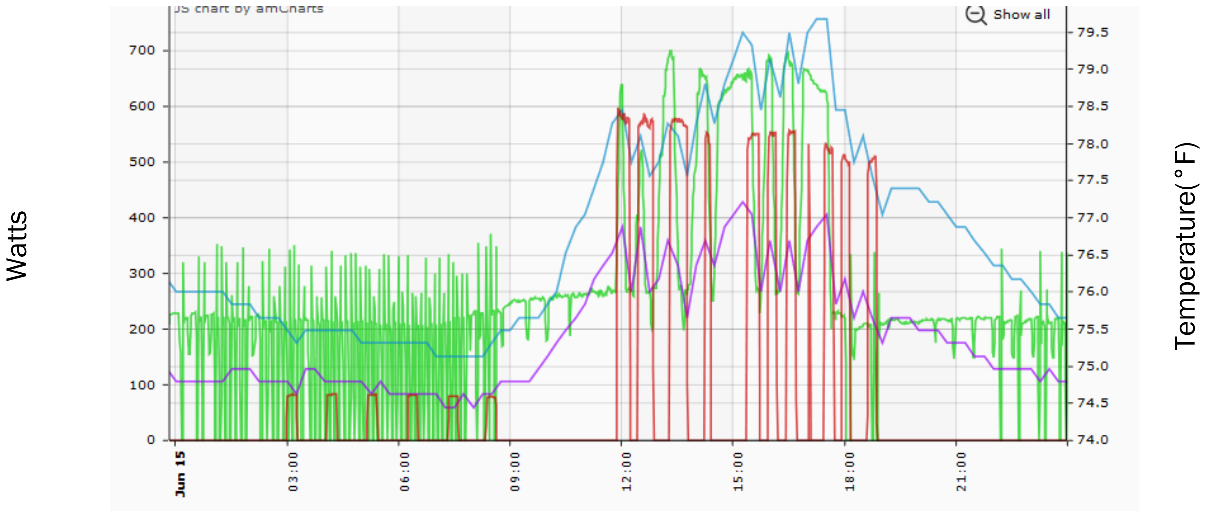

Figure 7. Site 8 post-intervention cooling profile: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

Pre-intervention, the MSHP cycles a lot during evening and early morning hours, and runs at a relatively low-capacity state, drawing mostly between 200 and 300 W. The short cycling appears to occur during hours with relatively low cooling load, resulting in the set point being quickly achieved. Post-intervention, the MSHP cycles much less during evening and early morning hours and runs constantly during the day and into the late evening when it starts to cycle on and off. The slightly lower MSHP set point is enough to keep the system from short cycling some of the time. Daytime operation is at a higher capacity, higher power state. As a result, several CSCS cycles are avoided. Fifteen-minute central system fan cycling during sleeping hours (3 a.m. to 9 a.m.) appears to bring the master bedroom temperature close to the living room temperature; it is warmer, but by less than 1°F. The occupant reported that he is comfortable, though sometimes the living room gets a little overcooled during the day and he powers down the MSHP. Ideally, during the day, the occupant would set the central system higher to achieve comfort. This is another example of supporting additional energy use savings that could be achieved with an integrated controller.

We re-evaluated cooling energy savings and room-to-room comfort after we collected about three months of data after the set point intervention. The energy use savings were normalized using a linear regression model using average daily outdoor temperature to predict cooling energy use. We applied the average outdoor temperature during the evaluation period, 83°F, to the model, which yielded a 10% cooling energy use reduction after the set point optimization. Results from this longer-term evaluation of cooling energy savings are more reliable than the brief evaluation conducted initially. Results are summarized in Table 7. The savings represent all hours of the evaluation period, whereas the temperature results compare the hours of fan cycling only.

Table 7. Site 8 Set Point Optimization Cooling Savings and Temperature Changes

Site 8	June–Oct 2017; 3–9 a.m.				June–Oct 2018; 3–9 a.m.			
HVAC Hours	Average	Max	%>3°F DT	n	Average	Max	%>3°F DT	n
Living Room RH	48.63				51.60			
Living Room T	75.39				75.24			
MBR Delta T	0.92	2.78	0.00	825	0.56	1.78	0.00	826
BR2 Delta T	0.42	1.57	0.00	825	0.81	2.35	0.00	826
BR3 Delta T	1.80	3.53	1.09	825	1.99	3.01	0.12	826
Cooling Energy Use (kWh/Day)	33.4				30.1			
Cooling Energy Use Savings	10%							

As with the pre-intervention period, the Delta T between the living room and master bedroom and the living room and second bedroom never exceeds 3°F. The temperature excursions between the living room and the third bedroom occasionally exceed 3°F during both pre- and post-intervention, but these occurrences are nearly eliminated post-retrofit. A similar evaluation was conducted at two other sites: at Site 4, the 3°F ACCA RS threshold was never reached, and at Site 15 the threshold was exceeded, but this home conducted intentional zoning of the bedrooms.

5 Integrated Controller Design and Evaluation

5.1 Integrated Controller Design

An integrated controller that has the capability to control the MSHP in coordination with the central system settings has the potential to optimize energy savings of the supplemental MSHP approach. This was evident in the earlier research described in Section 3.1.

5.1.1 Minisplit Heat Pump Equipment

A 1-ton Mitsubishi MSZ/MUZ-GL-12NA minisplit heat pump with a nominal SEER rating of 23.1, HSPF of 12.5, and sensible heat ratio of 0.74 was installed in the three sites identified to test the integrated controller experiment, although only two of the sites were utilized for control experimentation due to a CSCS incompatibility with the eventual control design at one of the sites. All systems were made operational on August 1, 2018. The baseline setup for the supplemental MSPH was the same as the earlier study:

1. The indoor fan coil units were all installed in the main living area of the homes, close to the central system returns, though the exact location of the indoor fan coil was sometimes a compromise between owner preference and the project preference.
2. Owners were initially provided general instructions to set the MSHP 2°–4°F lower than they operate their central system and to adjust as they needed for comfort. (The equipment was installed during the cooling season.)

Two homes from the prior MSHP study were also used for the integrated controller evaluation. These home each have a 1-ton, Panasonic XE12PKUA minisplit heat pump with a nominal SEER rating of 25.5, HSPF of 12, and a sensible heat ratio of 0.88. Existing instrumentation at all sites receiving the new MSHP was modified to include MSHP submetering. Details on the four integrated controller evaluation sites' system capacities and efficiencies are provided in Table 8.

Table 8. Integrated Controller Evaluation Sites

ID	Living Area (ft^2)	Stories	CSCS Size (tons)	CSCS SEER	MSHP Size (tons)	MSHP SEER	MSHP Installation Year
7	1,978	2	3.5	15	1.0	25.5	2014
8	2,050	1	5.0	12	1.0	25.5	2014
13	2,554	1	5.0	16	1.0	23.1	2018
14	1,559	1	3.0	17	1.0	23.1	2018

5.1.2 Controller Hardware

Because all sites had received a Nest thermostat as part of their participation in FSEC's previous PDR study, our approach to integrate the independent MSHP and CSCS systems involved leveraging the internet connectivity of smart thermostats, and development of a cloud-based algorithm that would run on a web server at FSEC and read and write to the thermostats via application programming interface (API).

The controller hardware we deployed included updating existing Nest thermostats to a Nest Generation 3 smart thermostat with the capability of remote temperature sensing via a separate, wireless sensor to control the central system; a Sensibo wireless smart thermostat to control the MSHP in a fashion similar to the infrared signal on the MSHP remote control; and a Nest remote temperature sensor to allow set points to be accommodated in different rooms rather than only where the thermostat is positioned. Most occupants chose to locate their remote sensor in their master bedroom, although one site preferred to use a bedroom more distant from the main living area and with an eastern and southern exposure, which made it prone to warmer temperatures than the rest of the house. A schematic of the hardware components is shown in Figure 8.

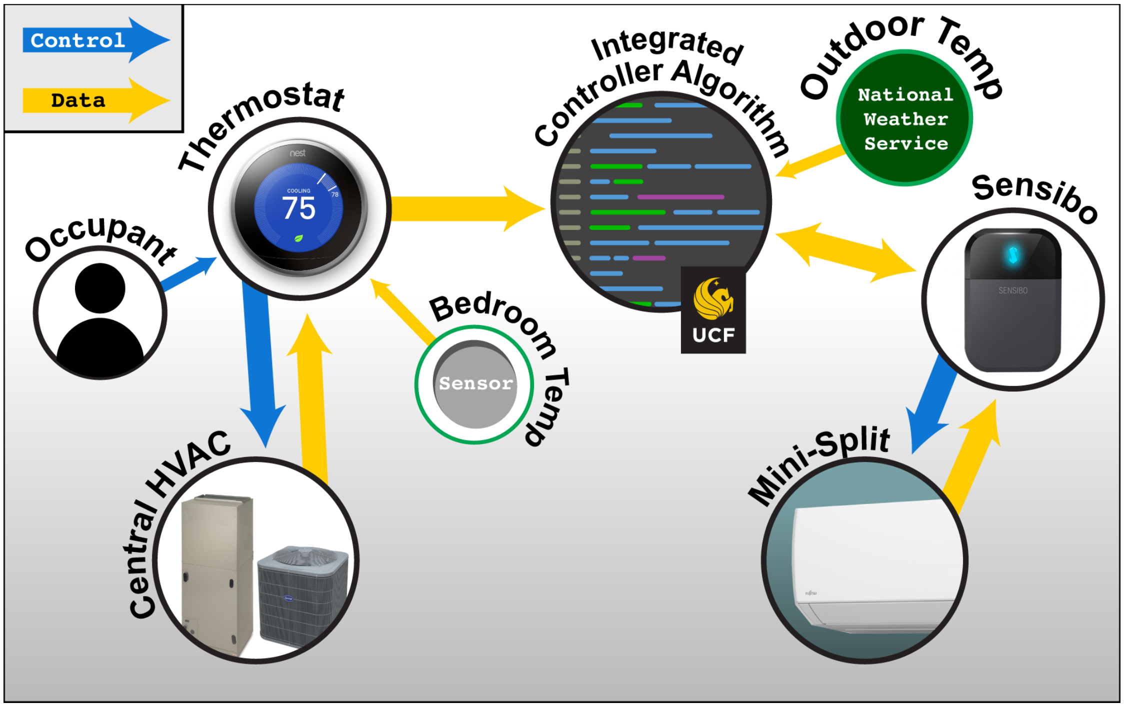

Figure 8. Integrated controller hardware design

The control approach involves the occupant controlling their central system thermostat as usual, with a programmable schedule. Occupants enter their desired cooling set point, and any desired setups/setbacks. During the day, the Nest is configured to read space temperature from its location in the main living space. During a nighttime block,[3] the thermostat is configured to read space temperature from the remote sensor in the bedroom to ensure sleep time comfort needs. On a 15-minute time step, our program reads the mode (heat/cool/auto), set point, and room temperature (living room or bedroom) via open API from the Nest thermostat and feeds it to the

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[3] Pre-set time blocks were built into the Nest thermostat app.

algorithm along with additional inputs including outdoor temperature from the National Weather Service station and time of day. The algorithm calculates a set point instruction for the MSHP, which is written to the Sensibo smart thermostat, which is controlling the MSHP. The algorithm also maintains the MSHP fan in “auto” via the Sensibo. While occupants can manually adjust MSHP settings, the algorithm regains control at the start of the next 15-minute time step. If the occupant continues to be uncomfortable with the MSHP operation, they are always able to override our control of the MSHP by disconnecting the Sensibo to stop the connection.

5.1.3 Controller Algorithm

Upon retrieval of the algorithm input data from both the Nest and Sensibo connected thermostats via API, the algorithm dynamically calculates the MSHP set point instruction as an offset from the central system set point as follows:

MSHP set point = CSCS_SP - (SO + AO) + NO, where

CSCS_SP = Central system set point

SO = Standard offset, a static input value

AO = Additional offset, which varies with outdoor temperature and is defined as OT – CSCS_SP/TR

OT = Outdoor temperature

TR = Temperature response denominator, a static input value

NO = Night offset, a static input value optionally applied during sleeping hours

In general, the algorithm seeks to dynamically adjust the MSHP set point below that of the CSCS for cooling (“dynamic droop”) to ensure the MSHP use is maximized and CSCS use is minimized, up until the point comfort could be sacrificed. FSEC built a simulation in Microsoft Excel that used TMY3 weather data to evaluate the controller algorithm response to the different input variables, so that we could tune the inputs with manual, iterative simulation runs to produce MSHP set point results we deemed reasonable. A common set of optimized inputs was initially applied to all test homes. Customized adjustments were later applied to some homes to improve performance; these result from differences in home characteristics and occupant behavior. More detail is provided in Section 5.4. We envision that a commercially available control could be designed with a universally applicable set of algorithm inputs, while still allowing for some customization by contractors and homeowners.

Figure 9 is a plot to demonstrate the dynamic response of the MSHP set point during two days of cooling. In this example, the MSHP set point instruction is somewhere between the CSCS set point and 8°F cooler. Note that during more mild outdoor temperatures and nighttime, the MSHP set point does not vary much from the CSCS set point. Contrary, during warmer hours and daytime, the algorithm calculated MSHP set point instruction is as much as 8°F lower than the CSCS set point.

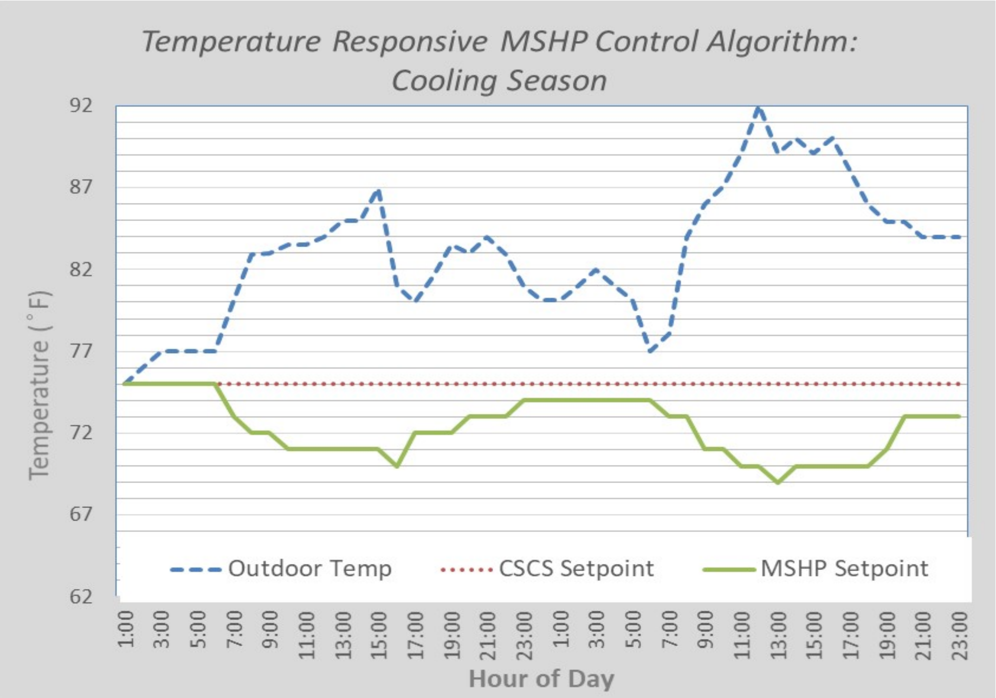

Figure 9. Integrated controller algorithm applied to synthetic cooling season data

Although this research focused on cooling, we designed the algorithm to consider other seasons. In anticipation of swing seasons, where it is possible that homeowners may switch from cooling to floating to heating over the course of a few days, we inserted fail-safe code to ensure that the MSHP was not cooling when an occupant set their central system to heat, nor heating when the occupant set their central system to cool. Central Florida's mild weather during winter did not permit heating performance to be measured in our study, but we did evaluate the algorithm with simulations to see how it might be used to generate heating energy savings. Figure 10 shows the simulated results during a two-day cold snap, and applies the same algorithm inputs for Standard Offset, Additional Offset, Temperature Response Denominator, and Night Offset as used in Figure 9 for cooling. The plot demonstrates that the algorithm is responsive to heating.

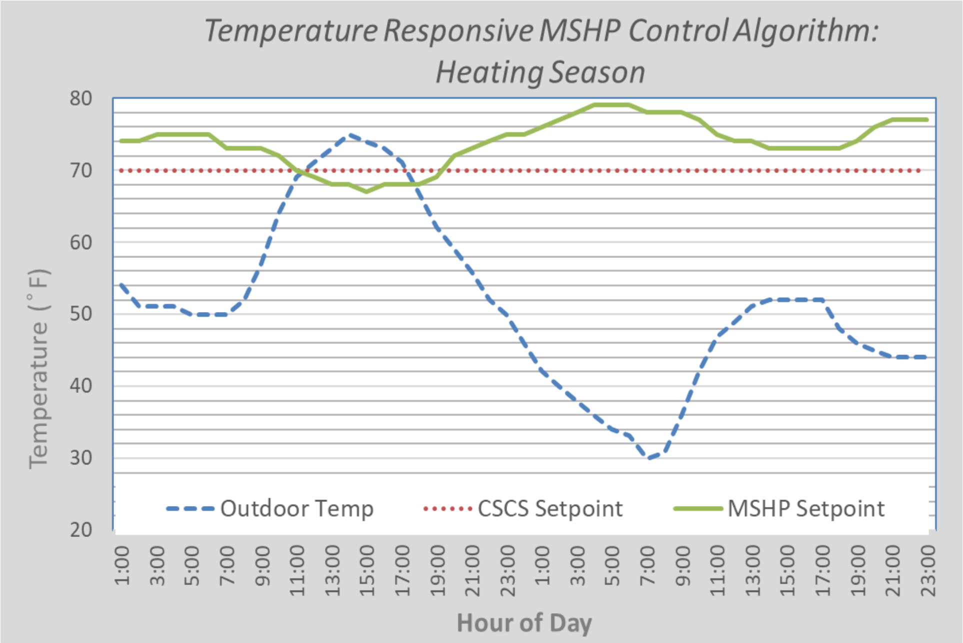

Figure 10. Integrated controller algorithm applied to synthetic heating season data

5.2 Evaluation Method

Integrated control of the evaluation sites' systems began in May 2019. The initial algorithm inputs used were those derived from the algorithm simulation assessment. We began a process of reviewing: (1) the algorithm controller logs (interior and exterior temperatures, CSCS and MSHP set point instructions, and other thermostat stored details), and (2) 1-minute energy use signatures of the MSHP and CSCS as well as 15-minute interior temperatures in the living room and bedrooms. Our initial unrefined algorithm inputs were modified as we strove to reduce cooling energy use and maintain or improve comfort.

Continuous connectivity between the Sensibo and MSHP was initially a challenge at some sites. Connection was lost due to homeowner disconnection or relocation of the Sensibo, considering the Sensibo needs line-of-sight to the MSHP. Through the middle of summer, we worked with the occupants to reset connectivity and ensure comfort, while we customized each home's algorithm to improve or maintain comfort and maximize cooling energy savings.

For two of the integrated controller sites, Sites 7 and 8, the MSHP was installed in 2014. This provided ample baseline data during manual operation of the supplemental MSHP. MSHPs at Sites 13 and 14, however, were installed in the second half of the 2018 cooling season and were lacking baseline data. Site 13's occupants were manually very aggressive with their MSPH from the moment of installation, minimizing the run of their central system to the point of failing to maintain comfortable bedroom temperatures as they had prior to the MSHP installation. While they achieved great initial savings, given the change in temperature distribution throughout the home, their use did not provide a representative "standard operation" baseline to measure the integrated controller against. Site 14's occupants, like some in the prior study, needed time to learn how to adjust to using the MSHP—sometimes turning the MSHP off for days, and occasionally heating with the MSHP while the central system was cooling, likely because they had it in “auto” mode. For these reasons, we were unable to collect enough baseline data during the 2018 cooling season for Sites 13 and 14. In place, we implemented a two-week “flip” period during the 2019 cooling season integrated controller experiments.

Regardless of the baseline period length, the energy savings projection method involved developing a linear regression model for each site, using average daily outdoor temperature to predict total daily HVAC energy. This approach is recommended by ASHRAE for retrofit evaluation (Haberl et al. 2005). (Delta indoor-to-outdoor temperature was not considered as an independent variable for this evaluation because interior temperatures were altered as the result of the experiment, e.g., the living room may have been intentionally overcooled at times as a result of trying to limit CSCS runtime.) Where data supported a long-term evaluation, the resulting model was applied to the local area TMY3 cooling season (May–October) weather data. For the sites where we had limited baseline data and the resulting model would not be applicable to the entire cooling season, we applied the results to one representative average daily summer temperature, 80°F.

5.3 Results

5.3.1 Cooling Energy and Demand

The cooling energy savings generated by the integrated controller, beyond savings achieved from the addition of the MSHP, were as high as 16% and are the result of the refined algorithm developed over time for each site. A discussion of lessons learned during the algorithm refinement process is included in Section 5.4. Savings indicate a reduction in total cooling energy using the integrated controller over a baseline of supplemental MSHP being operated independently by occupant. Results from the refined regression models and savings results are provided in Table 9.

Table 9. Cooling Energy Use Savings of Integrated Controller vs. Manual Operation of Central System Plus MSHP

ID	Manual Operation (CSCS+ MSHP)		Integrated Control		Savings	
	R^2	Seasonal Cooling Energy May–Oct (kWh)	R^2	Seasonal Cooling Energy May–Oct (kWh)	Seasonal Cooling Energy (kWh)	%
7	0.61	4,670	0.60	4,120	634	11.8
8	0.56	3,467	0.47	3,052	415	12.0
	Adj. R^2	Daily Cooling Energy at 80°F (kWh)	Adj. R^2	Daily Cooling Energy at 80°F (kWh)	Daily Cooling Energy (kWh)	%
13	0.54	17.7	0.81	20.4	(2.7)	(15.3)
14	0.71	12.8	0.73	10.7	2.1	16.4

Annual cooling energy savings at Sites 7 and 8—11.8% and 12.0%, respectively—are the result of the more robust regression model based on longer-term data. Savings at Sites 13 and 14 are limited in that they compare two weeks of an imposed manual operation with two weeks of the integrated control. These short periods do not allow for a full cooling season projection. The energy use results from these two sites are vastly different, showing negative cooling savings at 80°F of -15.3% at Site 13 and 16.4% at Site 14. The negative savings at Site 13 were not surprising given the homeowner was very involved in trying to minimize his central system energy use during the "flip" period under his control (manual operation). Further, during the integrated control period, better bedroom temperature control was achieved.

Using Site 14, we demonstrate the energy profiles for both the MSHP and CSCS for a midsummer day during manual operation (Figure 11) and during integrated control (Figure 12). Under manual operation we see a lot of CSCS energy during the day, always triggering the MSHP to reduce power or even shut off. Under integrated control, the MSHP carries the load from 12 a.m. until midafternoon.

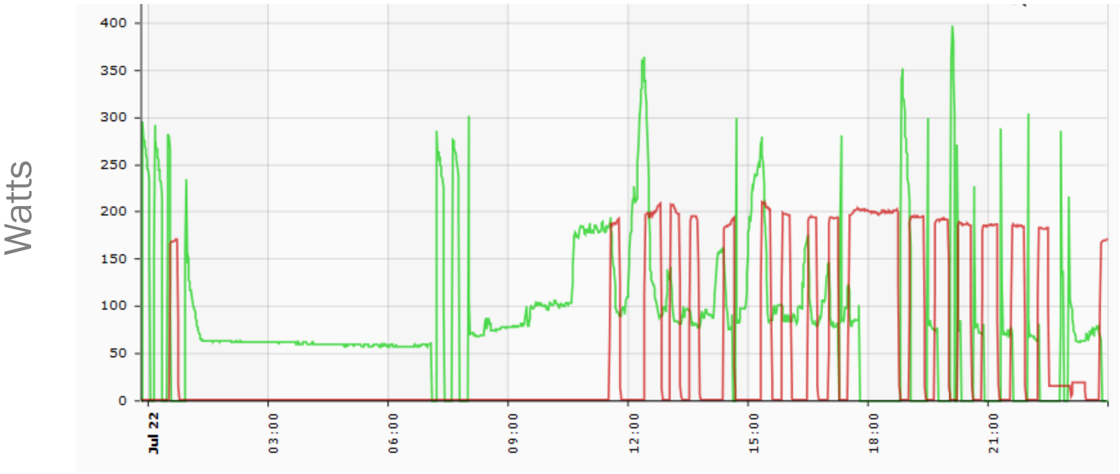

Figure 11. Site 14 MSHP and CSCS energy profile under "manual operation": CSCS power/10 (red), MSHP power (green)

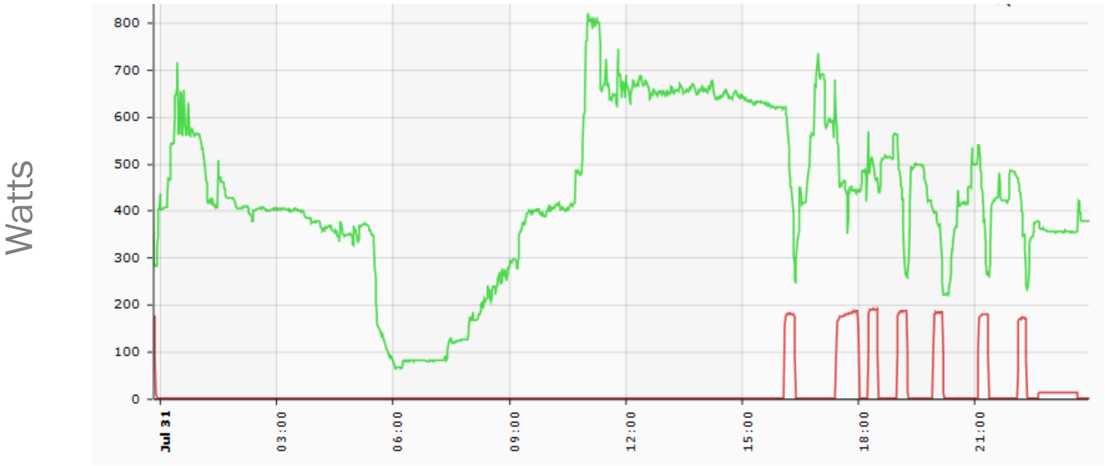

Figure 12. Site 14 MSHP and CSCS energy profile under integrated control: CSCS power/10 (red), MSHP power (green)

5.3.2 Equivalent Full-Load Hours

We know from our own and prior referenced research that without integration of the two systems’ thermostats, installation of supplemental MSHPs does not result in maximum potential energy savings, largely as a result of falling short of their potential operating hours. To evaluate how runtime changed with the introduction of our integrated controller, we calculated the equivalent full-load hours of both the CSCS and MSHP for 12 sites, for all years available. As MSHPs are able to vary their capacity, looking at a simple runtime fraction is not as useful as with fixed capacity equipment, especially because the MSHPs in our study are not instrumented to collect data on delivered capacity. Analyzing equivalent full-load hours normalizes the MSHP runtime with respect to full capacity, and is a more useful metric.

The equivalent full-load hours calculation applied was:

> Cooling Season Average (System kWh / 98th Percentile of Power), Where
>
> 98th Percentile of Power = 98th percentile of 1-minute data for one full cooling season of system power for all sites of a specific model,[4]
>
> System kWh = Metered hourly energy use, and
>
> Cooling Season = May 1–October 31

The equivalent full-load hours calculation was conducted for all sites, for all equipment, and for all cooling seasons monitored (2013 on) that did not include a transition involving a supplemental MSHP. So, this includes years before the CSCS alone, years with the CSCS and unintegrated MSHP, and the year of CSCS and the integrated control of the MSHP. The results

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[4] 98th percentile is used rather than 100th percentile of power measured, which was found to occur only intermittently (for example, during startup operation) and did not deliver a corresponding amount of cooling capacity. 100th percentile is not always the most reliable estimate of duty cycles (Powers et al. 1991).

are provided in Table 10. One caveat to the summary below is that post-MSHP with control for both CSCS and MSHP reflects the entire 2019 cooling season and also brief flip periods for two sites. So, we expect that these results are slightly conservative.

Table 10. Equivalent Full-Load Hours for Multiple Sites

Equivalent Full-Load Hours (energy/max power 98 percentile; n=site years)	Average	Min	Max
CSCS			
Pre-MSHP (n=16)	32%	24%	42%
Post-MSHP, no control (n=25)	32%	15%	53%
Post-MSHP, with control (n=4)	18%	14%	26%
MSHP			
No control (n=25)	13%	1%	42%
With control (n=4)	41%	30%	50%

Site 7, with years of data, provides a nice example of this transition from CSCS only, to supplemental MSHP with manual control, and supplemental MSHP with integrated control. Site 7's CSCS and MSHP annual equivalent full-load hours are plotted in Figure 13. The equivalent full-load hours for the MSHP hovered around 10% in the years prior to the integrated control; with integrated control, the MSHP equivalent full-load hours exceed 40%, with a relative decline in CSCS equivalent full-load hours.

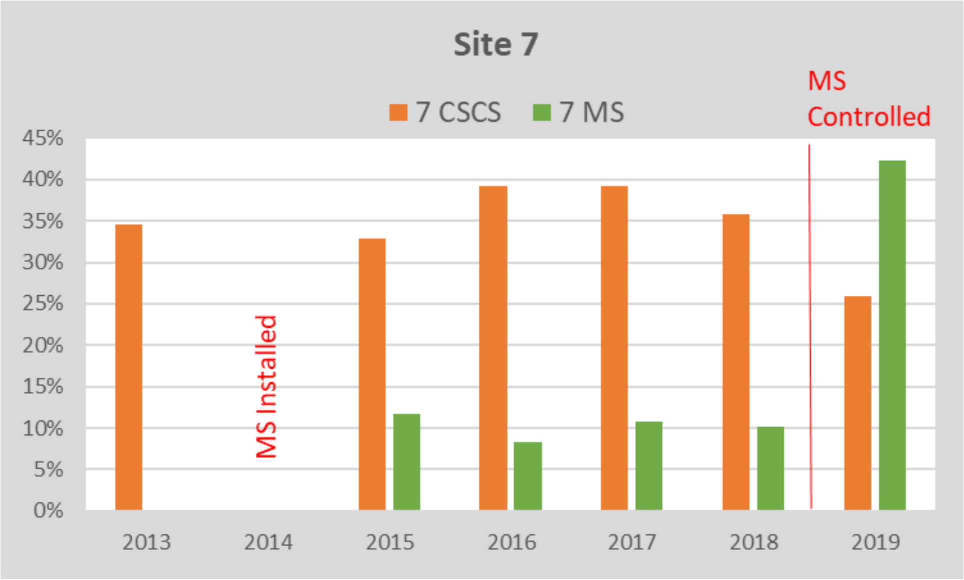

Figure 13. Site 7 equivalent full-load hours of existing systems from 2013–2019

5.3.3 Thermal Distribution

Because the home's thermal distribution is addressed differently under our integrated controller scheme, resulting in intentional zoning, a pre-to-post-controller temperature distribution summary comparison will not be instructive. What is important is that the occupants were always in control of their comfort; they could alter the set point on their Nest, they could disconnect the Sensibo to control the MSHP directly, and they could (and did) provide feedback to help us to modify the algorithm settings specifically for their needs. More discussion on the integrated controller impacts temperature distribution is included in Section 5.4.

5.3.4 Relative Humidity Control

The integrated controller tended to control interior RH better than the manual operation of the CSCS and MSHP. For Sites 8 and 14, the improvement in RH was large, with daily average indoor RH reductions exceeding 4%. The exception in this trend was as at Site 7 where the RH increased, though only by about 1% on average. This home had the lowest RH for the baseline period, likely due to their low nighttime set point resulting in more system runtime. The average daily RH for manual operation versus integrated control for these sites during their respective cooling seasons is displayed in Figure 14. Data for these plots are generally from July–October and matched to account for where data was sparse (e.g., for sites with shorter baseline periods). To avoid mild days where windows may have been opened, we excluded days when the average daily outdoor temperature was below 75°F.

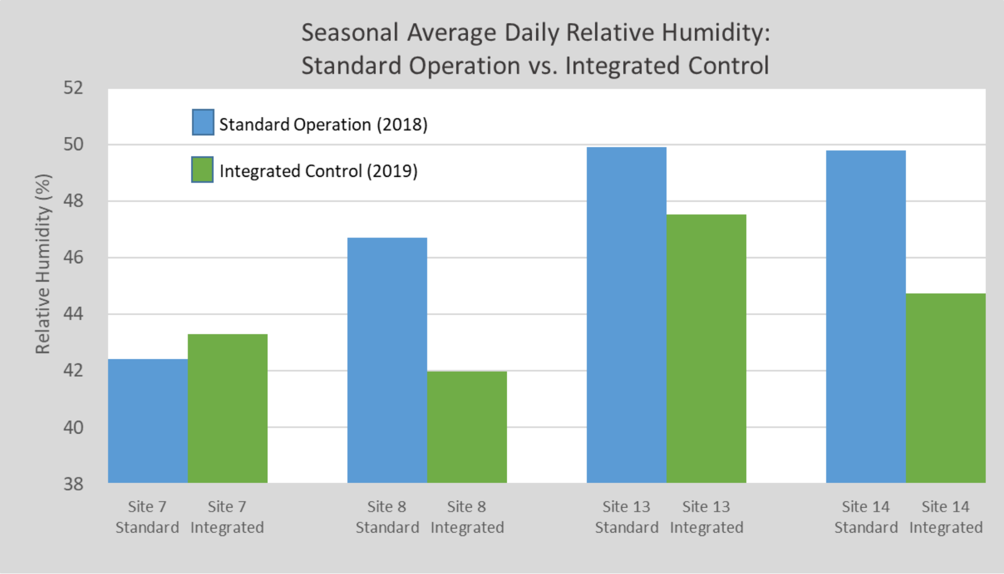

Figure 14. Average daily RH for the 2018 (standard operation) and 2019 (integrated control) cooling seasons.

5.4 Algorithm Refinement Process: Discussion and Lessons Learned

When we initially enabled the integrated controller in the field test homes, we applied the algorithm inputs selected during the TMY3 simulation process described in Section 5.1.3. We refined those inputs over time based on collected data to improve the performance, both in terms of temperature control and energy savings. Some improvements we made wholesale (applying to all sites), and others were applied to individual sites.

Increasing the MSHP use and reducing CSCS use is how the integrated controller scheme saves energy. This shift impacts thermal distribution throughout the house in a couple of ways. The main living area where the MSHP is located can become overcooled by a couple of degrees as the controller tries to deliver whole-house comfort without the use of the CSCS. Most occupants reported this, but it did not rise to the level of discomfort. Bedroom, office, and bonus room temperatures are allowed to float warmer than they would with a CSCS running exclusively and distributing conditioned air directly to all zones. This is manageable to occupants however because the control gives them the ability to schedule this around their preferences. Typically, occupants were willing to allow the bedrooms to be a little warmer during the day, and they used the bedroom temperature sensor to force the CSCS to maintain comfort during the hours bedrooms are typically occupied. Figure 15 and Figure 16 display this general trend for Site 14, which achieved 16.4% annual cooling season energy savings. Each plot shows energy use and temperature profiles for one day. Our example days each had average daily outdoor temperatures of about 83°F. Figure 15 is during manual operation, and Figure 16 is integrated control. Focusing on temperature only, it is notable that with the integrated controller the master bedroom temperature (in light blue) is a little cooler during sleeping hours, while the living room temperature has a similar profile each of these days. These two days also provide a good example of how the MSHP energy (green) maintained these temperatures while greatly reducing CSCS energy (red).

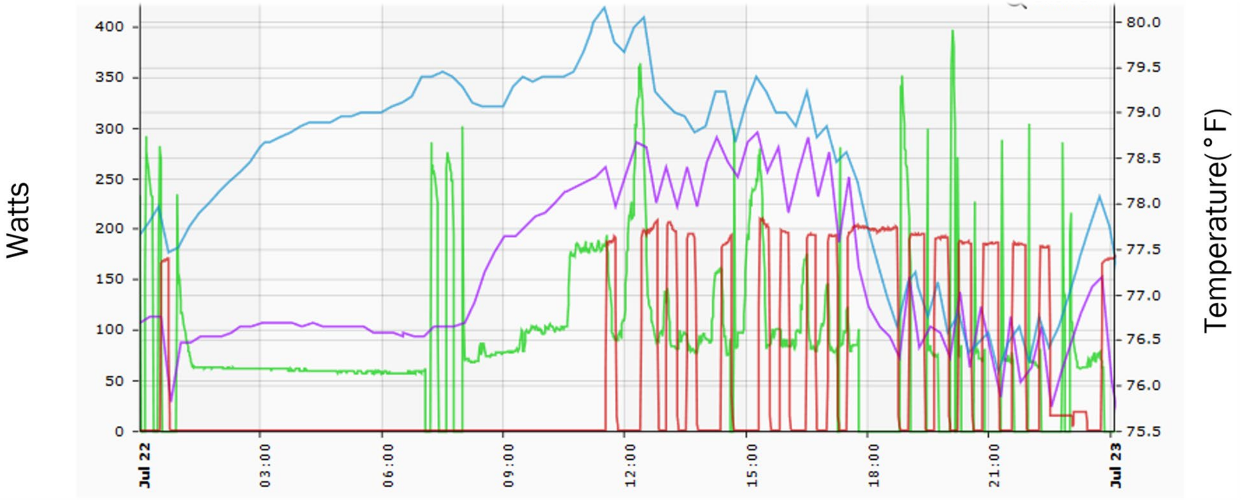

Figure 15. Site 14 energy and interior temperature profile during standard operation: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

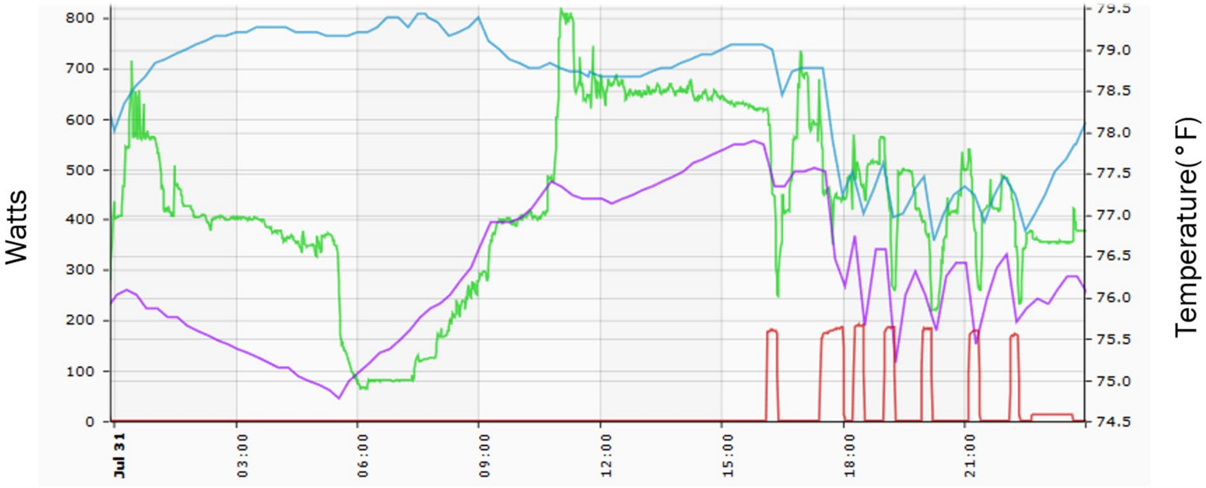

Figure 16. Site 14 energy and interior temperature profile during integrated control: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

5.4.1 Bedroom Temperatures Too Warm

Site 7 is unique in that it is the only two-story home in the study. With the bedrooms on the second floor, it is not surprising that this site experienced the highest indoor bedroom temperatures during the day while the controller scheme was operating off of the Nest's first-floor sensor. Site 7 is also unique in that (1) the occupants desire a very low temperature for sleeping (65°–70°F) and (2) one of the occupants works an odd schedule and often requires the bedroom comfortable for intermittent daytime sleeping. Figure 17 displays the profile when using standard algorithm inputs with master bedroom temperature in purple, which exceeds 80°F in the late afternoon to early evening. The occupant's programmable thermostat schedule reduces the desired set point from 75°F during the day to somewhere between 65° and 70°F at night, causing extended CSCS runtime beginning just before 9 p.m., until just after 3 a.m. Although bedroom excursions of 80°F or more may be possible when the occupants desire a return to 75°F for sleeping, a return to 65°–70°F for sleeping is too much.

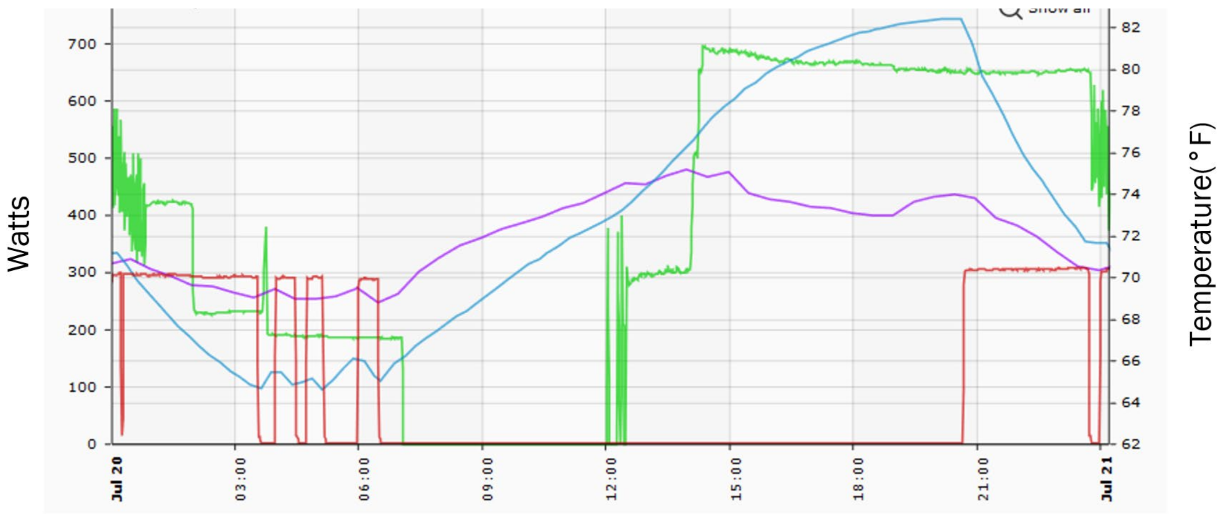

Figure 17. Site 7 energy and interior temperature profile: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

Ultimately, a customized adjustment made at this site was to have the Nest always look to satisfy the remote sensor in the bedroom, coincident with a slightly warmer set point to keep the lower level from becoming overcooled. Figure 18 demonstrates results with this different approach. Notable changes are that the living room temperature is about two degrees warmer at its extreme in the early morning hours, aligning with master bedroom temperature, and the bedroom temperature is kept cooler during the day. Also, we see more CSCS power cycling, especially in the morning hours, but we still see near flat-out MSHP power for much of the day and evening. (We caution to read too much into subtle differences between these two plots as they represent two days about two months apart with different weather patterns.) It is likely this change in strategy—having the Nest always look to satisfy the bedroom sensor—should be applied to all situations with two-story homes with bedrooms on the second floor.[5]

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[5] We first tried to have the occupant lower the NEST set point when he desired lower bedroom temperatures during the day, but it took too long for the central system to achieve desired temperature.

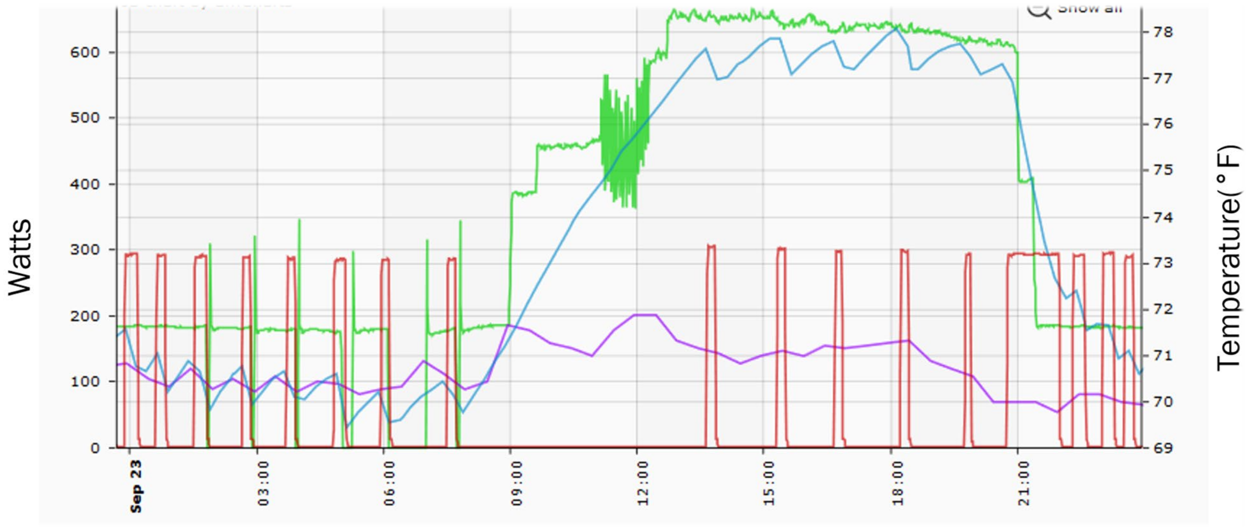

Figure 18. Site 7 energy and interior temperature profile with constant master bedroom sensing: CSCS power/10 (red), MSHP power (green), living room temperature (purple), master bedroom temperature (light blue)

5.4.2 Savings Eroded with Excessive Overcooling

One issue we encountered at a few homes was that the living room temperature was excessively overcooled (relative to standard or manual operation) during the early morning hours as the integrated systems worked to efficiently satisfy the bedroom set point during the night. Site 13 is unique in that it was the only home where our integrated controller scheme provided negative savings. Bear in mind that the occupants had different comfort requirements during the manual operation under their control and our integrated controller. The energy use and temperature profiles for one day under manual operation and one day under integrated control are provided in Figure 19 and Figure 20, respectively. Each day had a daily average outdoor temperature of about 83°F. One reason for the negative savings, as previously mentioned, was a result of the improved bedroom comfort provided by the integrated controller. Under manual operation (Figure 19), the occupants were allowing the bedroom temperature (blue line on plots) to approach 78°F during sleeping hours, though temperatures were more comfortable (75°–76°F) during the (presumably) unoccupied portion of the day. In contrast, under integrated control (Figure 20) the bedroom temperature was maintained between 74°F and 75°F overnight, and allowed to rise slightly during the day. Although keeping the bedroom cooler at night came at an energy cost, it does demonstrate that the integrated controller was better able to achieve comfort.

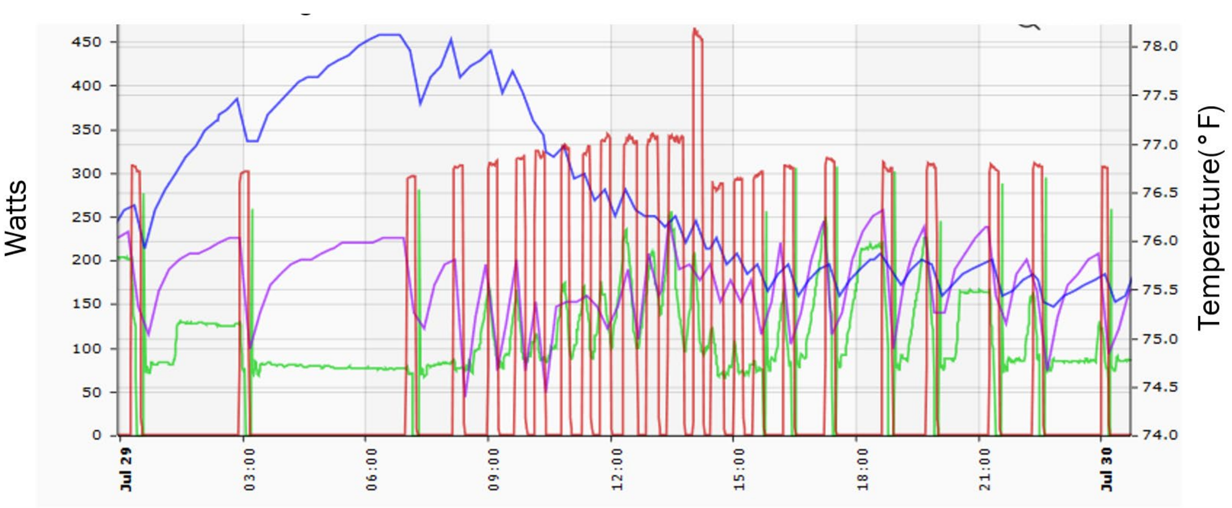

Figure 19. Site 13 energy and interior temperature profile during standard operation: CSCS power/10 (red), MSHP power (green), living room temperature (purple), distant bedroom temperature (blue)

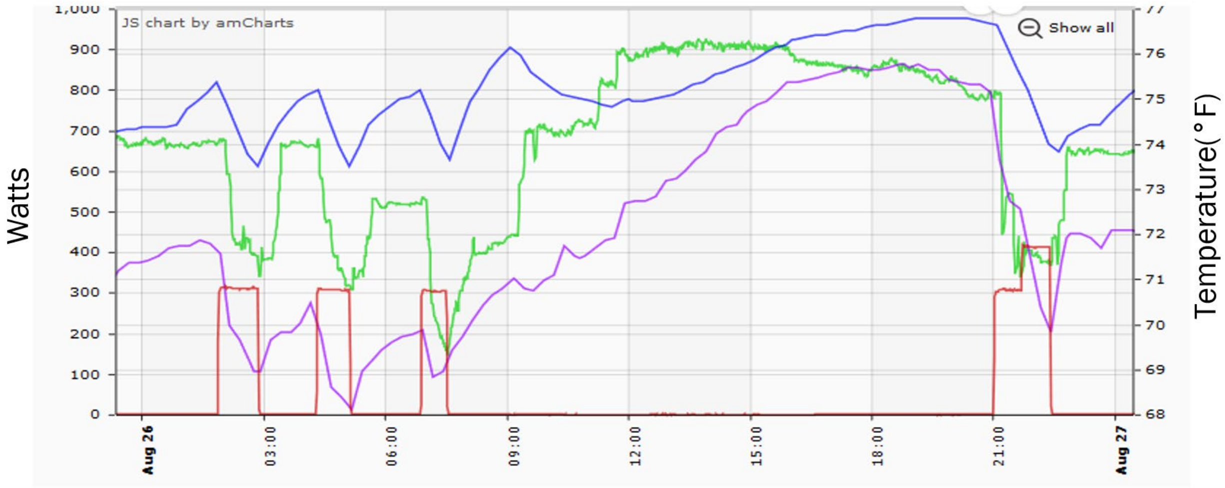

Figure 20. Site 13 energy and interior temperature profile during integrated control: CSCS power/10 (red), MSHP power (green), living room temperature (purple), distant bedroom temperature (blue)

It is also insightful to address the differences in the living room temperature (purple line on plots above). Most notable is how much cooler the living room is overnight while the thermostat is reading from the bedroom—generally about 76°F under manual operation, but sometimes below 70°F with the integrated controller. This is an example of overcooling with the MSHP. Furthermore, in a straight comparison between these two days, the increased MSHP power generated by the integrated controller that resulted in overcooling did not work to offset enough of the CSCS energy to generate HVAC savings.

It should be noted that at no site was the cooler living room temperature reported to be uncomfortable. Some amount of "overcooling" created by aggressively running the relatively more efficient MSHP can offset enough CSCS energy to generate savings. However, at some point, aggressively running the MSHP can result in pushing the MSHP into a high-capacity, low-efficiency state where the energy use required is not offset by the minor benefit from the overcooled central zone. Also, referring back to Figure 19 and Figure 20, we see that even though aggressive MSHP operation during the day was able to avert CSCS cycles, the prolonged high-power (900-W), low-efficiency operation also contributed to negative savings. Addressing each site individually, we reduced the nighttime offset as well as the standard offset in some cases (as at Site 13) to minimize or eliminate the living room overcooling, and scale back daytime MSHP operation to a lower power state. The ideal control design would have built-in customizability.

5.4.3 Influence of Outdoor Temperature on Controller Operation and Energy Savings

Across all sites that achieved savings, the integrated controller algorithm performed better (saved more energy) at more mild outdoor temperatures than it did at higher temperatures. For the one site that achieved negative savings, the trend was the same: the hotter days experienced more negative savings. In Figure 21, we demonstrate this point with Site 14, which had 16.4% savings at 80°F. Note that with an average daily outdoor temperature of 78°F, manual operation resulted in CSCS energy of 8.9 kWh, which was reduced by 6.2 kWh with the addition of 3.3 kWh of MSHP energy via the integrated controller for that day. Quite differently, during the 85°F day, the integrated controller reduced CSCS energy by nearly the same (6.7 kWh), but this time it took nearly as much MSHP energy (6.6 kWh) for that offset, nearly eliminating savings at the higher temperature.

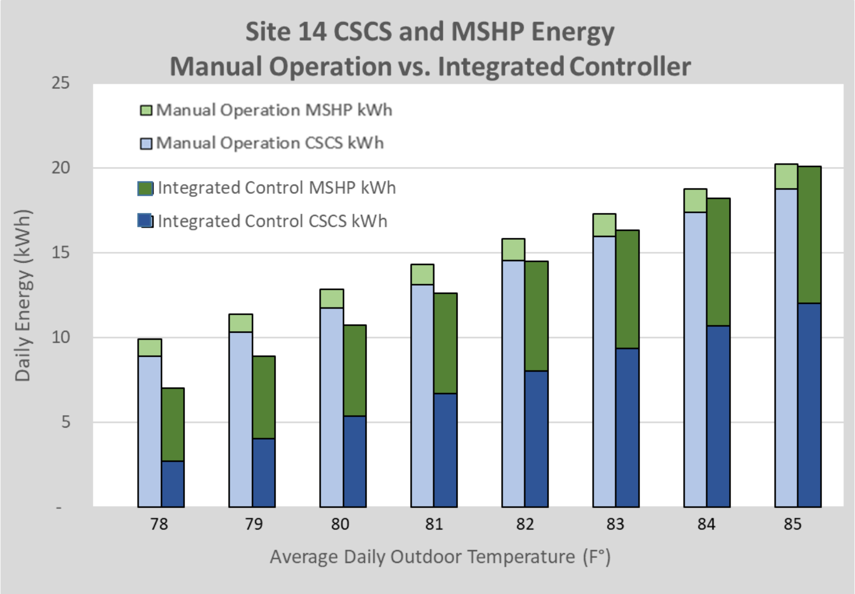

Figure 21. Outdoor-temperature-induced change in daily average CSCS vs. MSHP kWh composition for manual operation vs. integrated controller

This finding is explained, at least in part, by changes in the MSHP's efficiency at different capacities. We plotted the performance data of the MSHP used at this site, and we see that at higher capacity, its efficiency suffers. Figure 22 is the performance map of the Mitsubishi MSZ/MUZ-GL-12NA.

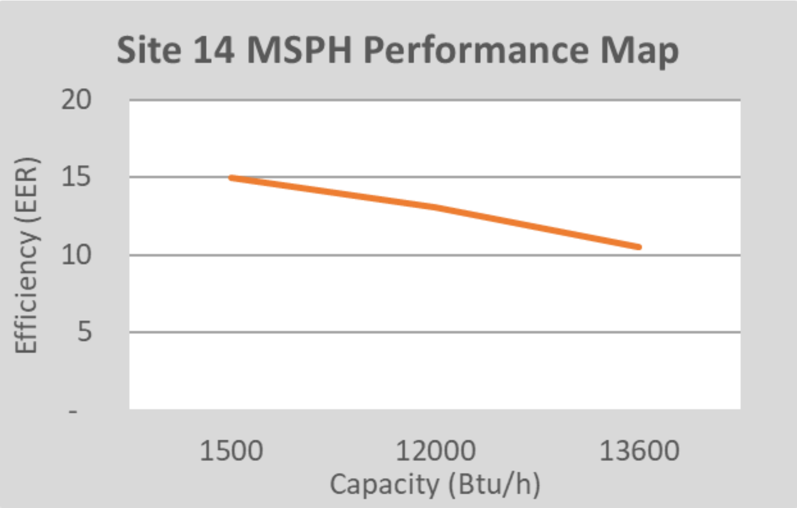

Figure 22. Mitsubishi MSZ/MUZ-GL-12NA capacity versus efficiency

The increase in MSHP capacity results from (1) warmer outdoor temperatures creating more load on the space and (2) the dynamic features of the algorithm that call for a lower MSHP set point with warmer outdoor temperatures. In Figure 23, we compare two days during integrated control. One day had an average temperature of 75°F, the other 85°F. The plot demonstrates how much more time the MSHP is working at higher capacity and a lower efficiency state.

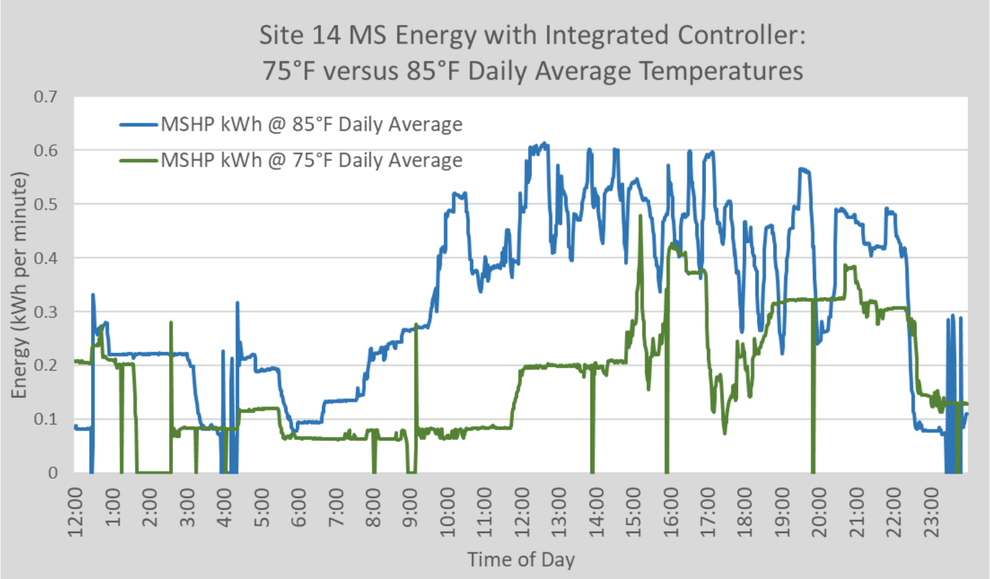

Figure 23. Site 14 MSHP energy use profiles for average daily temperatures of 75°F and 85°F

This trend in reduced savings, which can result in negative savings at even higher outdoor temperatures, suggests there is a peak outdoor temperature where our algorithm should be less aggressive with the MSHP power. At an average 3-ton peak load in the field homes, a 1-ton MSHP is never going to substitute for the CSCS, no matter how aggressively it operates; rather than push the MSHP to its limit, greater savings can be achieved by running it a bit more conservatively. While it is possible to optimize these adjustments for each site, exactly where the savings will go negative will likely be different depending on the unique setup and will be determined by the capacity, efficiency, performance map of both systems, and occupant behavior. Ultimately, a commercialized controller will need to make generalizations, but should still allow some customization by contractors or occupants through parameters such as the temperature response denominator, standard offset, etc. (refer to Section 5.1.3).

6 CSCS End-of-Life Simulations

Although the premise of the supplemental MSHP retrofit approach is based on the CSCS not yet being obsolete and having useful life left, at some point after installing a supplemental MSHP, the CSCS will need to be replaced. To investigate various options, we created a multizone residential model using EnergyPlus™ Version 9.2, DOE's whole-building energy performance simulation program. We conducted simulations under a variety of replacement scenarios, including abandonment of the central system for a wholly ductless solution. EnergyPlus will not allow simulations involving two thermostats in the same zone operating to two different set points, as required by our integrated controller scheme. Thus, our multizone simulation experiment is limited to manual operation of a supplemental MSHP, rather than incorporating our integrated controller design. Rather than utilizing differing set points, simulations were calibrated with field data as discussed in the following sections.

6.1 Building Model

A detached single-family existing house with four bedrooms, two bathrooms, and attached garage with total floor area of 2,996.7 ft^2 (278.4 m^2) and net conditioned floor area of 2,480 ft^2 (230.4 m^2) was used as a building model, closely representing one of the field homes. The conditioned spaces were grouped into three thermal zones for modeling purpose (see Figure 24). The three thermal zones were the living room, which includes the interior corridor and one of the bathrooms, a master bedroom with a bathroom, and the other two bedrooms were combined as the third thermal zone. The attached garage was modeled as an unconditioned thermal zone. The house had wood-framed exterior wall with assembly U-value of 0.112 Btu/hr-ft^2-F (0.636 W/m^2-C). The window glazing U-value and SHGC were 1.02 Btu/hr-ft^2-F (5.827 W/m^2-C) and 0.53, respectively. Window area to conditioned floor area ratio was 8.02%. The various internal gains of the house were split to the three thermal zones proportional to the floor areas.

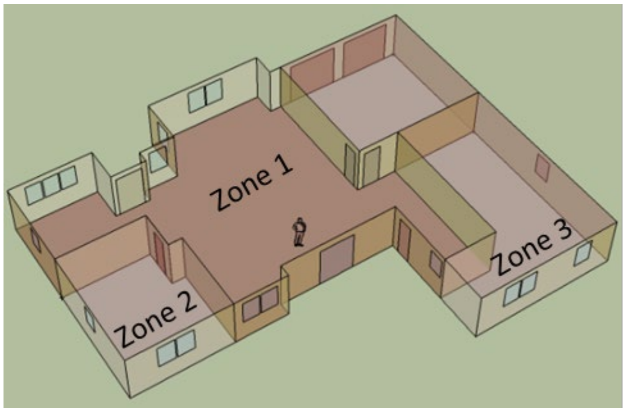

Figure 24. EnergyPlus Version 9.2 multizone model building sketch

6.2 HVAC Models

Four HVAC configurations were created and compared against a conventional ducted central HVAC system using EnergyPlus. The HVAC system types investigated are summarized in Table 11. The three advanced HVAC equipment configurations investigated were combinations of a ductless variable-speed MSHP and various CSCS systems. The CSCS types investigated were single-speed, two-speed, and variable-speed central air-source heat pumps. The MSHP provides cooling directly to the living room only, whereas the central systems provide cooling to all conditioned spaces. The central systems distribute the conditioned air to the three thermal zones according to fixed distribution fractions. The distribution fractions were determined based on the design cooling loads and calibrated with actual monitored field thermal distributions. The fourth HVAC test configuration was ductless two head variable-speed multisplit air-source heat pump serving the three thermal zones, and each head was controlled from separate thermostats in each thermal zone.

Table 11. Baseline and Advanced HVAC Equipment Test Cases Specifications

Configuration Name	MSHP Systems	CSCS Systems
Baseline	None	Single-speed air-source heat pump, 3-ton capacity, 14.0 SEER, and 8.5 HSPF
Configuration 1	Single head variable-speed, 1-ton capacity, 23.0 SEER, and 12.5 HSPF	Single-speed air-source heat pump, 3-ton capacity, 14.0 SEER, and 8.5 HSPF
Configuration 2		Two-speed air-source heat pump, 3-ton capacity, 16.0 SEER, and 9.0 HSPF
Configuration 3		Variable-speed air-source heat pump, 3-ton capacity, 18.0 SEER, and 9.5 HSPF
Configuration 4	Single head variable-speed, 1.5-ton capacity, 23.0 SEER, and 12.5 HSPF, and Two head variable-speed multisplit air-source heat pump, 1.5 ton (2 heads of 0.75 ton) capacity, 18.5 SEER, and 9.5 HSPF	None

The different configurations are defined as follows:

- Baseline: Multizone model with a single-speed central system serving all the three zones with a thermostat located in the living room. There is no MSHP.
- Configuration 1–3: A multizone configuration with an MSHP as a first priority; equipment controlled from a thermostat located in the living room. The CSCS is controlled from a thermostat located in the living room during the day, and the same CSCS controlled from a thermostat located in the master bedroom at night.

- Configuration 4: A multizone, all-ductless configuration with a ductless head serving each zone.

6.3 HVAC Control and Operation Sequence

Because there are two sets of HVAC equipment serving the living room, there is a need to determine sequence of operation of the two sets of HVAC equipment such that their impact resembles performance data observed from the field. For this purpose, the variable-speed minisplit air-source heat pump was always run as the first priority, whereas the central system heat pump was run as a second priority. The central system heat pump was enabled in the simulation when the minisplit reached 75% capacity. An iterative procedure was used to arrive at this value, and was based on matching zone temperature differences in the model with those identified in the study homes (see Section 3). As an additional measure to ensure simulated temperature distribution matched that of the monitored field data, we devised a scheme involving a second CSCS that would only operate if the master bedroom temperature was going out of range. We used an energy management system[6] program to control the central systems operation from two different thermostat locations. In order to allow the central systems control from the two thermostats, an identical copy of the central system HVAC model was added in the EnergyPlus input deck for each of the three advanced control test cases.

The result was that each input deck of the three advanced test cases had two identical (virtual) copies of the central air-source heat pump system, called *Central System Mode 1* and *Central System Mode 2*. Having two identical virtual models of the central system allows it to run in two operating modes. *Central System Mode 1* was controlled from the living room thermostat and *Central System Mode 2* was controlled from the master bedroom thermostat. The operating sequence of the central system modes was determined based on cooling requirements of the living room and master bedroom. When *Central System Mode 1* is on, *Central System Mode 2* must be off because the two operating modes represent one physical set of equipment. Furthermore, *Central System Mode 2* had higher priority than *Central System Mode 1*. While the cooling set point for *Central System Mode 1* was 75°F*, Central System Mode 2* operation was triggered only when the master bedroom air temperature exceeded 78.8°F (26.0°C). The central system control switched between operating modes 1 and 2 as needed and was handled dynamically using an energy management system program. For the all-ductless test cases, the thermal zones had cooling set point temperature setbacks applied to take advantage of the zoning potential with this type of system. The living room thermostat cooling set point was setback to 78.0°F (25.56°C) from 9 p.m. to 7 a.m., and the bedrooms thermostat cooling set point was setback to 80.0°F (26.67°C) from 7 a.m. to 9 p.m.

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[6] The Energy Management System is high-level control methods available in EnergyPlus and used to provide additional control flexibility.

6.4 Results

The modeling results suggest that space-cooling energy use is reduced very little with a high-efficiency supplemental MSHP and with an end-of-life CSCS transition from a 14 SEER single-speed CSCS (Configuration 1) to the 16 SEER two-speed CSCS (Configuration 2), saving only 4% annually, or $15. Choosing the more efficient 18 SEER variable-speed CSCS (Configuration 3) appears unattractive too, saving only 8%, or $31 annually. Neither of these options make sense based on cost-effectiveness given the premiums for either higher-efficiency system. These findings are unsurprising, however, given that the highly efficient MSHP with no duct losses is providing the bulk of the building cooling load, leaving significantly less load to be met by the CSCS, effectively reducing the efficiency gains. The all-ductless scenario is more promising, with results suggesting 25% annual cooling energy savings, or $251. Although the premium for an all-ducted installation would still outweigh these savings, other considerations such as enhanced zoning ability, room-by-room temperature customization, and added redundancy could be other reasons for choosing this configuration. A summary of the simulation results are provided in Table 12.

Table 12. Simulated Cooling Energy Savings by Configuration

Cooling End Use	Baseline	Configuration 1	Configuration 2	Configuration 3	Configuration 4
kWh	4,634	3,385	3,261	3,130	2,541
kWh Savings Over No MSHP		1,249	1,373	1,504	2,093
% Savings		27%[b]	30%	32%	45%
Estimated Annual Savings $[a]		$150	$165	$181	$251
kWh Savings Over Configuration 1			124	255	844
% Savings			4%	8%	25%

[a] Savings are estimated using $0.12 per kWh.

[b] Note that these savings are a bit lower than those measured in the field, but determined sufficient for comparison of configurations.

7 Conclusions and Next Steps

Previous research has shown that installing a modest-capacity, centrally located, high-efficiency, ductless MSHP for use in conjunction with an existing home's CSCS provides a low-cost space-conditioning upgrade solution that reduces energy use and energy cost with no impact on occupant comfort. A previous 10-home study conducted by FSEC in central Florida documented median energy savings of 33% (6.7 kWh/day) for space cooling (with savings ranging from 21%–46% for nine homes and one home at 2%) and 59% (6.5 kWh/day) for heating (with savings ranging from 19%–82% for eight homes, one home at 9%, and one home with no pre-retrofit heating data), for a total annual space-conditioning energy savings of 34% (with savings ranging from 20%–50% for nine homes and one home at 4%). Longer-term data were subsequently analyzed for three of these homes, and space cooling energy savings in the range of the 10-home study have been shown to persist year over year. Cooling energy savings have also been shown to be repeatable with three additional MSHP installations achieving cooling energy savings within the 10-home study range.

The current research described in this report involved integrating control of a CSCS and a supplemental MSHP in four homes. Without an integrated controller, we found that manual operation of the two independent systems resulted in sporadic and nonoptimal MSHP operation as occupants sought to maintain relatively even temperature throughout the home. To do so, MSHP operation acting to cool the main body needed to be sufficiently scaled back or eliminated at certain times of the day in order for the CSCS thermostat, located in the main body of the homes, to respond and deliver air to bedroom zones. Analysis shows that a dynamic integrated controller solution that adjusts MSHP operation based on outdoor temperature and occupant schedules achieved as much as 16% cooling energy savings compared to manual operation of the systems without an integrated controller. The cooling energy savings ranged between 12% and 16% in three of the homes, and savings were found to be -15% in one home that did not maintain equivalent indoor temperatures during the experiment. Our controller design showed the ability for better comfort control, and the experiments provided highly informative lessons instructive in continuing to improve controller performance.

The integrated controller algorithm and hardware components provided energy savings by forcing the ductless, high-efficiency MSHP to operate more while reducing runtime of the less-efficient, ducted CSCS. The algorithm's energy savings success is attributed to specific areas of integration, including (1) slightly overcooling the main room in the early morning hours with the MSHP, which delayed the need for the CSCS engagement, minimizing or avoiding MSHP short cycling, and (2) by introducing more MSHP runtime, including during sleeping hours without jeopardizing bedroom comfort.

Considering results obtained through past and current research, we expect that installation of a modest-capacity, centrally located, high-efficiency, ductless MSHP together with a dynamic controller that integrates operation with the home's existing CSCS by adjusting MSHP operation based on outdoor temperature and occupant schedules can achieve cooling energy savings in the range of 12%–60%, depending on a number of factors including climate, system efficiencies and occupant comfort preferences. Although this research focused on cooling, we designed the algorithm to consider heating as well. Central Florida's mild weather during winter did not permit heating performance to be measured, but we did evaluate the algorithm with simulation and showed that with similar algorithm inputs, it would also be able improve heating energy savings beyond the 19%–82% achieved in the previous FSEC study involving installation of an uncontrolled MSHP. Important overall project lessons include:

- Special controller considerations should be given to two-story homes with bedrooms on the second floor to keep bedrooms from approaching uncomfortably high afternoon temperatures.
- A market-ready integrated controller solution can be offered with generalized algorithm input parameters, but should also include the flexibility to be customized to address the different needs of occupants and housing characteristics (e.g., to avoid overcooling of the main living area or a lack of cooling to a peripheral room, both of which occurred given specific behaviors and housing characteristics).
- Overworking supplemental MSHP can erode savings. Cooling set points aggressively lower than the CSCS can force the MSHP to run near maximum output for extended periods, which reduces performance enough to eroding savings. Cooling energy savings from the integrated controller was found to be consistently larger (both in terms of kWh and percent) at milder outdoor temperatures.
- CSCS fan cycling to improve whole-house temperature distribution with a supplemental MSHP cooling the main living area provides minimal benefit compared to necessary energy expenditure for homes with ducts in unconditioned space.
- Installing the MSHP too close to the CSCS supply air can create control issues.
- Continuous connectivity between the Sensibo and MSHP was initially a challenge at some sites. Connection was lost due to homeowner disconnection or relocation of the Sensibo to a location that was not within line of sight of the MSHP. Through midsummer 2019 we worked with the occupants to reset connectivity and ensure comfort, while we customized each home's algorithm to improve or maintain comfort and maximize cooling energy savings.

Savings documented through experimentation in the occupied homes more than justify an anticipated added cost for a commercialized controller. Hardware costs for the controller used in these experiments was approximately $400, which could result in a simple payback of 5 years given 16% seasonal cooling energy savings vs. manual control. As previously mentioned, simple payback for the addition of the MSHP itself is expected to improve as markets mature and more incentives become available. However, it is important not to discount some intangible benefits of the supplemental MSHP approach:

1. The benefit of system redundancy if the CSCS fails due to need for repair or replacement. The MSHP can continue to provide some level of comfort, extending the amount of time the occupants have to make a reasonable choice for CSCS repair or replacement.
2. The ability of an intelligently controlled system to provide demand response benefits to a utility by temporarily disabling the CSCS while the MSHP continues to provide comfort.

Both of these benefits are demonstrated in Figure 25. In this case, one of the sites from FSEC's original PDR study lost use of their CSCS during summertime, but were comfortably able to get by until the system could be replaced.

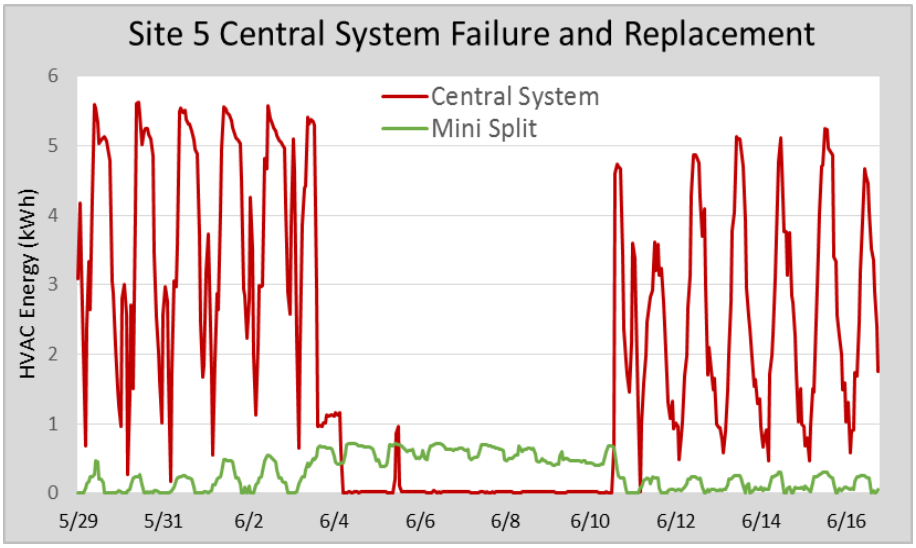

Figure 25. Occupants increased use of MSHP (green) while replacing CSCS (red) that had reached end of life. This is representative of how a utility may act to control systems for demand response.

The end-of-life simulations conducted to investigate the most cost-effective options for what to do when the CSCS expires suggest that as long as the ductless, more efficient MSHP is able to address much of the building load (as seen in our field experiments), replacing the CSCS with the least efficient model available is most cost-effective. A multiheaded ductless configuration could also be a consideration for such reasons as enhanced zoning ability, room-by-room temperature customization, and system redundancy; cost-effectiveness alone would not be a reason to choose this option.

As more and more homes are integrating supplemental minisplits with conventional air-conditioning systems, the energy efficiency industry is becoming broadly aware that better integration between the systems is necessary for optimal efficiency and comfort. Utilities transitioning to electric heating fuel for more renewable integration and price stabilization are incentivizing control integration of such a system design, though the best solutions will be climate specific and are still being investigated.

FSEC supports several fronts toward the goal of better integrated control solutions across climate zones. We are currently involved in a study (2019–2021) funded by The New York State Energy

Research and Development Authority (NYSERDA) and lead by The Levy Partnership, which aims to maximize the heating savings from supplemental ductless heat pumps by demonstrating how integrated controls can manage the interaction with gas furnaces and hydronic systems. The Consortium for Energy Efficiency has invited our research team to join their recently launched integrated HVAC controls working group, whose goals are to identify opportunities, technology status, market barriers, and market development needs. We have also served as advisors to the Pacific Northwest National Laboratory for their laboratory and simulation research on supplemental MSHP and integrated controls for heating applications.

Future work includes partnering with manufacturers and refining our copywritten controller algorithm to incorporate what we have learned into a user-friendly product that would allow customers to control two independent systems with one third-party thermostat, maximizing their comfort while reducing space-conditioning energy. Utility partnerships may also be sought, as the algorithm could be modified to target demand reduction.

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