Who's Leading: The Dance Between Mini-Splits and Existing HVAC Systems

Cheryn Metzger, Travis Ashley, Yan Chen, Karthikeya Devaprasad, Jaime Kolln, and Zhihong Pang, Pacific Northwest National Laboratory
Karen Fenaughty, Eric Martin, and Danny Parker, Florida Solar Energy Center
Jordan Dentz, The Levy Partnership
David Lis, Northeast Energy Efficiency Partnerships
Christopher Dymond, Northwest Energy Efficiency Alliance
Greg Sullivan, Efficiency Solutions

ABSTRACT

Recently, many utilities across the U.S. have provided incentives for ductless mini-split heat pumps due to their relatively high efficiencies. However, when these ductless mini-splits are installed in existing homes, utilities and researchers find that they are not living up to their energy saving potential, due to a lack of coordinated controls with the existing HVAC system. The Pacific Northwest National Laboratory (PNNL), the Florida Solar Energy Center (FSEC), and The Levy Partnership are all leading projects across the country to address this problem. The goal for this body of work is to determine which control strategies provide the most energy savings, for the least amount of resources, while maintaining comfort throughout the home. The three projects include research in PNNL Lab Homes in Richland, WA, field validation studies in Florida and New York, and model extrapolation across the country. The results of these studies can provide input for utilities who are considering incentivizing DHP control strategies in the living room area of existing homes that still have original heating and cooling systems in place. The results of these studies to date show that using a central or zonal system set-back control strategy saves a substantial amount of energy compared to other strategies. Additionally, although the complex control strategy saves a substantial amount of energy as well because only "occupied" areas are conditioned, the strategy is much more error prone and therefore less likely for the savings to persist.

Background

Ductless mini-splits are a technology which should hypothetically, save a substantial amount of energy over most heating and cooling equipment that they replace. A recent study by the Pacific Northwest National Laboratory (PNNL) showed that ductless mini-split heat pumps (DHPs) are modeled to save about 62 to 77% of heating energy in typical electric resistance baseboard heated Northwest homes (Metzger et al. 2018). Another study measured the savings from DHPs in the central living zone of 14 electric baseboard heated homes in the Pacific Northwest, which saved an average of 4,442 kWh per year (Geraghty et al. 2009). In the second year, 11 of these homes showed an average per-site savings of 4,204 kWh (Geraghty et al. 2010).

However, some studies show that when this equipment is installed in existing homes where the older system is left in place, the hypothetical savings potential is not reached. For example, a Northeast U.S. study of 152 homes retrofitted with DHPs showed that as a result of controls the ductless mini-splits were only being used for 51-64% of their total potential operating hours (Korn et al. 2016). The study recommended that development of controls that allow ductless systems and primary thermostats to interact and share information could lead to increased DHP savings. Similar experiments which studied DHPs installed in homes with electric resistance forced air furnaces in the Pacific Northwest resulted in an average savings of 5,500 kWh per year (Baylon et al. 2012a). This study also found that if the furnace were allowed to operate on its own control logic, it would overwhelm the operation of the DHP and result in little to no savings. These findings suggest that in order to produce significant savings where DHPs are retrofitted, the original furnace should be controlled so that the DHP acts as the primary heat source. Further studies by Ecotope in the Pacific Northwest show a similar issue with baseboard heaters. Ecotope suggests that even though DHPs are capable of providing most of the heat necessary for a home, the overall energy use remains higher than anticipated because the electric resistance heating is still acting as the primary heat source at night in the bedrooms (Baylon et al. 2012b).

In the Southeast U.S., The Florida Solar Energy Center (FSEC) conducted a field study of DHPs installed as a supplement to a central HVAC system in 10 homes in the cooling-dominated climate of central Florida. A one ton, 25.5 SEER, 12 HSPF, inverter-driven DHP was installed in each home as laterally near the central air conditioner return as aesthetically acceptable to the homeowner. Guidance to the occupants was to set the DHP thermostat 2°F-4°F lower than the central system for cooling, to set it higher by 2°F-4°F for heating. However they were allowed to operate the systems as they saw fit. This manual operation of the two independent space conditioning systems (DHP + central system) by the occupants demonstrated very promising heating and cooling energy savings. Documented median energy savings were 33% (2,007 kWh/year) for cooling and 59% (390 kWh/year) for heating, with large variation depending on the central system heating equipment (savings for homes with electric resistance were much greater than those with a heat pump) (Sutherland et al. 2016).

These recent studies have also shown that with DHPs installed in living rooms or another central location, comfort in bedrooms is a challenge. Sutherland et al. (2016) found that similarly, for homes in warm climates with centrally ducted air conditioning, a small capacity DHP in the living room is not able to maintain bedroom comfort overnight. One solution would be to add additional indoor heads to bedrooms to provide supplemental space conditioning so that electric resistance heating or central cooling would not be required at all. However, adding additional DHPs or heads would add to the cost of the installation. The studies by Ecotope showed similar results and used the electric resistance elements to heat the bedrooms in the Northwest U.S. at night to compensate for the DHP.

PNNL Lab Homes Project Scope and Results

PNNL, in partnership with Silicon Valley Power/American Public Power Association, Northwest Energy Efficiency Alliance, and Bonneville Power Administration, launched experiments in the PNNL Lab Homes to test various control schemes that would minimize heating and cooling energy use by optimizing the control of ductless mini-split heat pumps in conjunction with existing equipment.

PNNL initiated the Lab Homes project in 2011 to conduct experiments that evaluate the potential energy efficiency impact of new building technologies designed to reduce energy use. The lab homes are two identical 1,500 sq. ft., 3BR/2BA, all electric, manufactured homes located side-by-side on the PNNL campus in Richland, Washington (IECC Climate Zone 5/EIA Climate Zone 2). The homes were constructed to represent typical existing homes including R-11 wall and floor insulation and R-22 ceiling insulation. Energy use is monitored at all 42 breakers in each home and recorded using a Campbell Scientific CR1000 data logger that collects data at 1-minute intervals. A second CR1000 collects temperature readings at the same interval using 37 thermocouples that are distributed throughout the homes, including in every room, the hallway, and on both surfaces of all the windows.

For this investigation, both homes had the same make and model DHP installed in the living room. The outdoor units of the DHPs were installed in the back of each house on a 2’ × 2’ cement slab on stands and was about 1’ away from the house near the water heater closet access door. Figure 1 shows the location of the indoor and outdoor components of the DHP as well as the central system in each home. The indoor head was mounted to the wall between the dining room and living room about 1’ from the ceiling. An (Ecobee) thermostat for the central system was installed in the hallway on the wall across from the utility room, as marked by T1. The controller for the DHP was mounted on the wall below and to the side of the air handler unit, which is also the temperature sensor for the DHP, and is indicated by T2.A remote temperature sensor for the thermostat was placed in the master bedroom for some of the experiments (T3).

The DHPs were sized to meet about 69% of the cooling load and 113% of the heating load as calculated using EnergyPlus.[1] The rated capacity of the Mitsubishi MUZ-FH18NA is 17,200 Btu/h for cooling and 20,300 Btu/h for heating at 47°F.

There were two sets of experiments that were conducted. The “central system” experiments used an electric resistance central forced air furnace (FAF) for heating with a central air conditioner (AC) for cooling as the baseline. The central system heating, cooling and air conditioning (HVAC) components are shown in Figure 1. The central system ducts are located in the crawlspaces. The duct leakage was tested before the heating season experiments in September 2018. The Baseline Home had leakage around 230 cfm at 25 Pa and the Experimental Home had duct leakage of about 145 cfm at 25 Pa. The contractor who measured the duct leakage (and also checked for any disconnections or other impactful issues) mentioned that a lot of leakage om the Baseline Home did seem to be coming from the air handler cabinet itself.

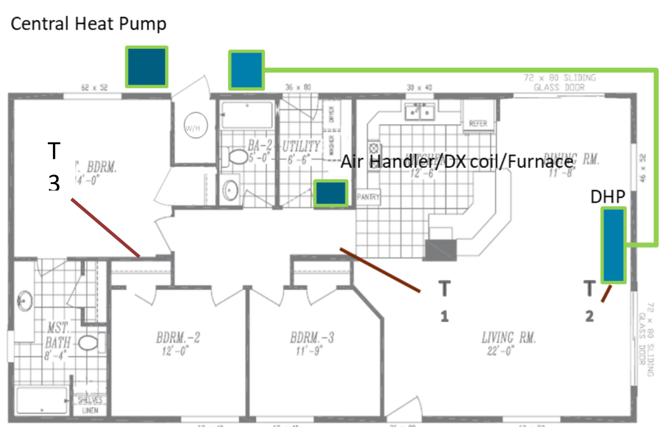

Figure 1. Central Heating/Cooling Lab Homes setup. *Source:* PNNL 2020.

The “zonal system” experiments used electrical resistance zonal heaters and window ACs as the baseline. The zonal heating and cooling experiments had a slightly different setup. Window

[1] EnergyPlus is a whole building energy simulation program developed with support from DOE: https://energyplus.net/.

ACs and space heaters were installed in each of the bedrooms, and powered fans were installed above the bedroom doors. This setup is shown in Figure 2 below.

Figure 2a. Zonal Heating Lab Homes setup; Figure 2b. Zonal Cooling Lab Homes setup. *Source:* PNNL 2020.

The variation between the "Baseline" Home and the "Experimental" Home in this study was the strategy by which the homes were controlled. These experiments were designed to replicate potential installations in people's homes. Each experiment was selected for promising and cost-effective solutions as determined by the program advisory committee. Table 1 shows a summary of the test setup for each experiment. The experiment title reflects just the control strategy for the experimental home.

Table 1. Summary of experimental set-up

Experiment Set: Experiment Title	Baseline Home			Experimental Home			Notes
	DHP Set Point(s)	Central Set Point(s)	Door status	DHP Set Point(s)	Central Set Point(s)	Door Status	

Experiment Set: Experiment Title	Baseline Home			Experimental Home			Notes
Central Heating: Fan Only	Off	72°F	Open	72°F	Continuous operation of central system fan. No heat.	Open	
Central Heating: Central Offset	Off	72°F	Open	72°F	67°F	Open	
Central Heating: Complex Schedule	Off	72°F	Open	See Table 2	See Table 2	Open	
Zonal Heating: Bedroom Setback	85°F	85°F	Closed	85°F	60°F Day 80°F Night	Closed	Raised set point due to rising outdoor temperature
Zonal Heating: Transfer Fans	85°F	85°F	Closed	85°F	Off, just transfer fans on at night	Closed	Raised set point due to rising outdoor temperature
Zonal Heating: Complex Schedule	85°F	85°F	Closed	See Table 2	See Table 2	Closed	Raised set point due to rising outdoor temperature
Central Cooling: Fan Only	Off	76°F	Open	76°F	Continuous operation of central system fan. No cooling.	Open	
Central Cooling: Central Offset	Off	76°F	Open	76°F	80°F	Open	
Central Cooling: Complex Schedule	Off	76°F	Open	See Table 2	See Table 2	Open	

Experiment Set: Experiment Title	Baseline Home			Experimental Home			Notes
Zonal Cooling: Bedroom Setback	76°F	76°F	Open	76°F	Off Day 81°F Night	Open	Lesson learned from heating to open doors
Zonal Cooling: Transfer Fans	76°F	76°F	Closed	76°F	Off Day 81°F Night with Transfer fans	Closed	Lesson learned from heating to turn on central HVAC with setback for comfort
Zonal Cooling: Complex Schedule	65°F	65°F	Closed	See Table 2	See Table 2	Closed	Lowered set points due to decreasing outdoor temperatures

Table 2. Complex schedule for each experiment

	Central Heating	Zonal Heating	Central Cooling	Zonal Cooling
DHP Conditioning Main Living Area				
Occupied (7am – 9pm)	72°F	85°F	76°F	65°F
Unoccupied (9pm – 7am)	66°F	80°F	81°F	70°F
Central System/Zonal Electric or Window AC Conditioning the Bedrooms				
Occupied (9pm – 7am	66°F	80°F	76°F	65°F
Unoccupied (7am – 9pm	55°F	60°F	90°F	Off

Each of the 12 experiments listed in Table 1 resulted in a range of energy savings and comfort levels for the living room and master bedroom. Detailed results from the 12 experiments listed in Table 1 can be found in Ashley et al. (2020). The best combinations of energy savings and comfort for each set of experiments are provided in Table 3 as the "Recommended Control Strategy."

Table 3. Recommended control strategies for each set of experiments

Set of Experiments	Recommended Control Strategy
Central Heating	Offset (Grilles Closed)
Zonal Heating	Bedroom Setback or Complex Schedule
Central Cooling	Complex Schedule

Set of Experiments	Recommended Control Strategy
Zonal Cooling	Bedroom Setback or Complex Schedule

Florida Field Validation Project Scope and Results

The objectives of the current FSEC work, which was conducted in partnership with the U.S. Department of Energy Building America Program and Mitsubishi Electric, were to design and demonstrate an advanced controller that could integrate operation of the DHP and central system to maximize space conditioning energy savings and maintain desired occupant comfort. The occupied home study sites were from a previous FSEC study (not yet published) and are almost exclusively single-story and average about 1900 ft^2 living area. Homes were monitored to collect one-minute time-step energy end use and 15-minute temperature and relative humidity data. The homes' central systems nominal efficiencies range from 10 to 17 SEER and capacity from three to five tons. Several homes had the 25.5 SEER supplement DHP installed as part of the earlier study and three received a similarly configured one ton, 23.1 SEER, 12.5 HSPF DHP as part of this study. The DHPs were installed in the living room near the central return.

As no existing controllers were commercially available that addressed space cooling integration, FSEC devised an approach to demonstrate the benefits of integration. The approach to integrate the independent DHP and central systems involved leveraging the internet connectivity of smart thermostats. FSEC developed a cloud-based algorithm that would run on a FSEC server at FSEC and read and write to the thermostats via application programming interface (API).

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; a Sensibo wireless smart thermostat to control the DHP in a fashion similar to the infrared (IR) signal on the DHP remote control; and a Nest remote temperature sensor to allow setpoints to be accommodated in different rooms (namely a bedroom) rather than only where the thermostat is positioned.

The control approach involves the occupant adjusting their central system thermostat as usual, including use of a programmable schedule if desired. During the day, FSEC configured the Nest to read space temperature from its location in the main living space. FSEC configured the Nest to read space temperature from a 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 central system mode (heat/cool/auto), setpoint and room temperature (living room or bedroom) via the Nest API and feeds it to the algorithm along with additional inputs, including outdoor temperature read from a National Weather Service station and time of day. The algorithm calculates a setpoint instruction for the DHP, which is written to the Sensibo smart thermostat controlling the DHP. The algorithm also maintains the DHP fan in "auto" via the Sensibo. While occupants can manually adjust DHP settings, the algorithm regains control at the start of the next 15 minute time step. If the occupant continues to be uncomfortable with the DHP operation, they are always able to over-ride our control of the DHIP by disconnecting the Sensibo to stop the connection.

Upon retrieval of the input data from the Nest and Sensibo thermostats, the algorithm dynamically calculates the DHP setpoint instruction as follows:

DHP setpoint = central system_SP - (SO + AO) + NO, where
central system_SP = Central system setpoint
SO = Standard offset, and is a static input value
AO = Additional offset, which varies with outdoor temperature and is defined as OT – central system_SP/TR
OT = Outdoor temperature
TR = Temperature response, and is a static input value
NO = Night offset, and is a binary (on or off) static input value

In general, the algorithm dynamically adjusts the DHP setpoint below that of the central system to ensure the DHP use is maximized in order to minimize central system operation up until the point comfort could be affected. 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. This integrative process was conducted separately for cooling and heating with differences in the standard offset and night offset. Only cooling results are discussed in this paper.

Integrated control was launched in four homes in May 2019 and evaluated through October for cooling season performance. In two of the integrated controller sites the DHP had been installed in 2014 and provided ample baseline data during the "manual operation" of the supplemental DHP. Results for these sites are representative of a whole cooling season. The other two sites had DHPs 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. For these sites, a two-week "flip" period was invoked during the 2019 cooling season experiments to collect additional baseline data. Results for these sites represent daily energy use differences at an average outdoor temperature of 80 °F. Regardless of the baseline period length, the energy savings projection developed a linear regression model for each site, using average daily outdoor temperature to predict total daily HVAC energy. This approach is recommended by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) for retrofit evaluation (Haberl et al. 2005).

The cooling energy savings generated by the integrated controller, beyond savings achieved from the addition of the DHP, were as high as 16% and represent the results of a refined algorithm developed for each site throughout the 2019 cooling season. Savings indicate a change in cooling energy using the integrated controller over a baseline of supplemental DHP operated independently by occupant. Results from the refined regression models and savings results are provided in Table 4.

Table 4. Cooling Energy Use Savings of Integrated Controller vs. Manual Operation of Central System Plus DHP

DHP Installation Year	Manual Operation (Central + DHP)		Integrated Control		Cooling Energy Savings	
	R^2	Seasonal Cooling Energy May-Oct (kWh)	R^2	Seasonal Cooling Energy May-Oct (kWh)	Seasonal kWh	%
2014	0.61	4,754	0.60	4,120	634	13.3
2014	0.56	3,467	0.47	3,052	415	12.0

DHP Installation Year	Manual Operation (Central + DHP)		Integrated Control		Cooling Energy Savings	
	Adj. R^2	Daily Cooling Energy at 80°F (kWh)	Adj. R^2	Daily Cooling Energy at 80°F (kWh)	Daily kWh	
2018	0.54	17.7	0.81	20.4	(2.7)	(15.3)
2018	0.71	12.8	0.73	10.7	2.1	16.4

Annual cooling energy savings for the longer-term evaluation sites were 13.3% (634 kWh) and 12.0% (415 kWh). Savings at the sites with recently installed DHPs were vastly different from each other, with one showing negative cooling savings at 80°F (an average daily outdoor temperature in Florida during the cooling season) of -15.3% (-2.7 kWh) and the other showing 16.4% (2.1 kWh). The negative savings were not surprising given this 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 DHP and central system energy profiles for mid-summer days under manual operation (Figure 4) and integrated control (Figure 5) are below. Figure 4 shows that, under manual operation, a lot of central system energy (in Red) is used during the day, and central system events trigger the DHP to reduce power or even shut off (in Green) – a typical pattern of the independently controlled systems as described earlier. Conversely, Figure 5 demonstrates that under integrated control, the DHP can carry the load from 12:00AM 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.

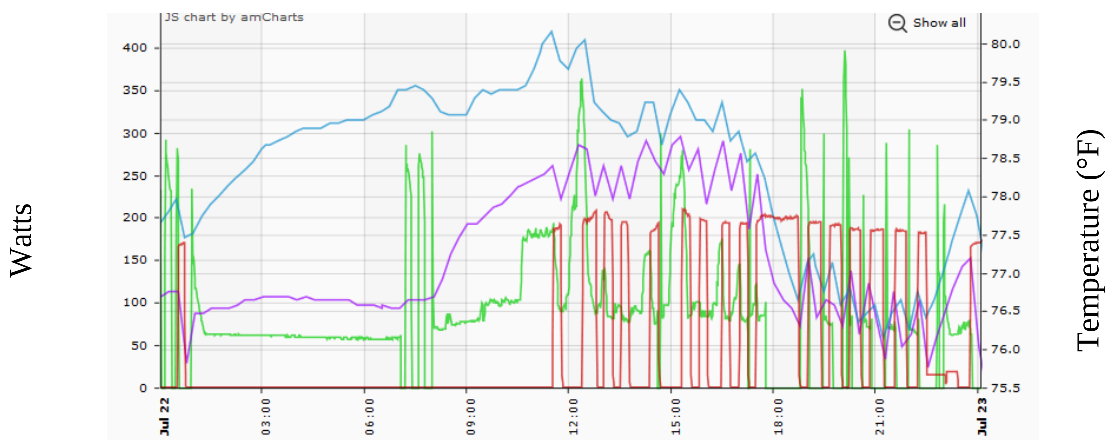

Figure 3. DHP and central system energy profile under 'manual operation': central system power/10 (red), DHP power (green), living room temperature (purple), master bedroom temperature (light blue). *Source:* FSEC 2019.

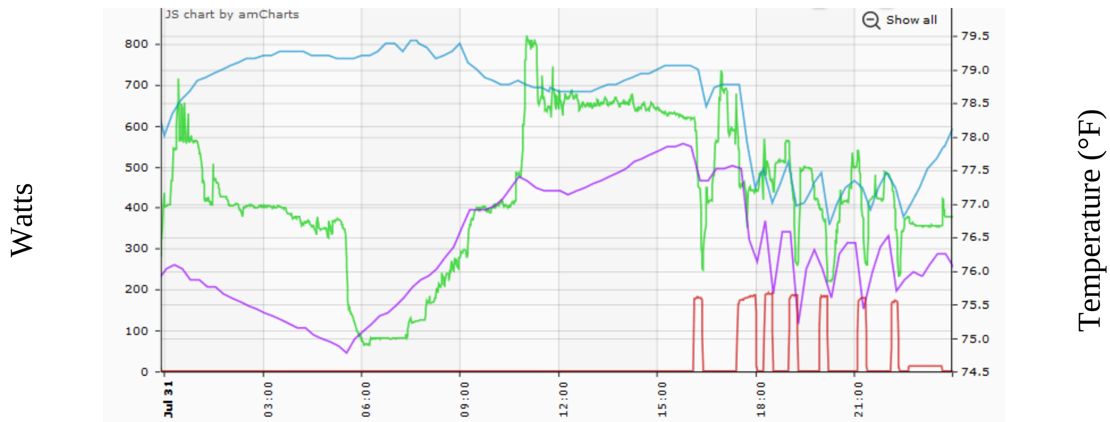

Figure 4. DHP and central system energy profile under integrated control: central system power/10 (red), DHP power (green), living room temperature (purple), master bedroom temperature (light blue). *Source*: FSEC 2019

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. What is important is that the occupants were always in control of their comfort; they could alter the setpoint on their Nest, they could disconnect the Sensibo to control the DHP directly, and they could (and did) provide researchers feedback to help modify the algorithm settings specifically for their needs. For example, there was a specific adjustment to the integrated control design at the two-story home to address very warm afternoon bedroom temperatures. Regarding relative humidity, the integrated controller tended to keep levels lower than the manual operation of the central system and DHP, averaging nearly 5% lower at two sites.

Data on runtime of the DHP were analyzed to see if it increased with the integrated controller. As DHPs are able to vary their capacity, looking at a simple runtime fraction is not as useful as with fixed capacity equipment, especially since the DHPs in this study were not instrumented to collect data on delivered capacity. Analyzing equivalent full-load hours (EFLH) normalizes the DHP runtime with respect to full capacity and is a more useful metric. To evaluate how the runtime changed with the introduction of our integrated controller, the EFLH of both the central system and DHP were evaluated for all 12 sites, for all years available. EFLH was calculated by first reviewing an entire cooling season to find the maximum power a system consumed for one minute. Then for every hour, the monitored energy for a given system was divided by 98th percentile[2] of power measured for a given minute during the full cooling season review. This was conducted for years with the central system alone, years with the central system and unintegrated DHP, and the year of central system and the integrated control of the DHP. The results are provided in Table 5 and show not only a large reduction in the average central system EFLHs with the integrated controller, but a stark increase in average DHP EFLHs as well.

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2 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).

Table 5. Equivalent full-load hours for multiple sites

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

New York Field Validation Project Scope and Results

PNNL, FSEC, The Levy Partnership and the Northeast Energy Efficiency Partnerships recently teamed up to use lessons learned from the previous two studies and apply that knowledge to the New York area. When discussing which control strategy seemed to be the most cost effective and persistent based on the two previous studies, a few factors were considered. Per the PNNL study, both the offset and complex schedule strategies appeared to be the most beneficial. FSEC had used a more complicated version of the offset control strategy which was no longer possible. Unfortunately, the results from the FSEC experiment were developed when Nest had an API available which could pull from various inputs to create flexible set points for the central thermostat based on both an offset from the DHP, and outdoor temperature. However, without that Nest API capability, the team agreed to test two strategies in New York using Mass Save approved Integrated Controls Packages.[3] The first strategy would be the offset strategy, and the second strategy, would be to use the outdoor temperature as a trigger for the central system to come on when necessary.

The Levy Partnership and FSEC have started to collect detailed data on central and DHP system energy use, runtime, indoor environmental conditions, and outdoor environmental conditions in New York homes with and without the integrated control system operating over alternating periods. A total of twelve homes, with a mix of hydronic and forced air central systems will be enrolled in this study that is supported by the New York State Energy Research and Development Authority (NYSERDA). The Levy Partnership also aims to collect pre- and post- retrofit (DHP installation) utility data as well as conduct interviews to collect occupant feedback on the control strategies.

This project is ongoing, and no results are available to date.

Model Extrapolation Project Scope and Results

The modeling study used the data from the PNNL Lab Homes (including air infiltration and weather data such as dry-bulb and wet-bulb temperatures, wind speed/direction, and solar radiation that were collected during the experiment) to calibrate the simulation model (using

[3] https://www.masssave.com/-/media/Files/PDFs/Save/Residential/Integrated-Controls-and-Dual-Fuel-TStats_Master.pdf.

EnergyPlus v8.9) and extrapolate the results to different climate locations and different building sizes. A multizone model was developed in order to attempt to capture the effects of both systems and understand the comfort implications of certain control strategies in the bedroom areas. The zones used in the model calibration, are shown in Figure 6.

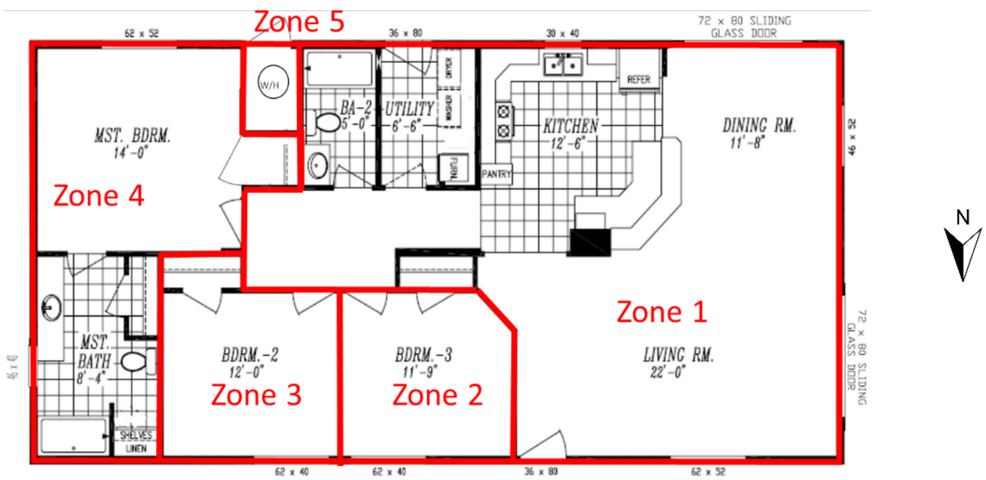

Figure 5. Lab Home floor plan and thermal zoning in the EnergyPlus model. *Source*: PNNL 2020.

Table 6. Building characteristics

Item	Description
Building	PNNL Lab Home
Vintage	Existing residential building
Location	Richland, WA, USA
Window fraction	South: 30%, east: 30%, north: 30%, west: 30%, average total: 30%
Thermo-characteristics	External wall: 0.535 $W/m^2.K$, Window: 3.127 $W/m^2.K$
Lighting load	6 W/m^2
Plug load	60 W/m^2

Table 7. HVAC system specification for EnergyPlus model

Equipment	Parameter	Equipment in Lab Home	EnergyPlus model	National Extrapolation
DHP	Model	MUZ-FH18NA	NA	NA
	Cooling capacity	5041 W	5041 W	Autosize
	Heating capacity	5950 W	5840 W	Autosize
	Fan efficiency	0.7	0.7	0.7
	Max air flow rate	0.351 m^3/s	0.351 m^3/s	Autosize
	Rated HSPF	12	12	12
	Rated SEER	22	22	22
	Cooling stage	3	1	1

Equipment	Parameter	Equipment in Lab Home	EnergyPlus model	National Extrapolation
	Heating stage	3	1[4]	1
Central System	Cooling capacity	8792W	8750 W	Autosize
	Heating capacity	8784W	Autosize	Autosize
	COP	3.81	3.81	3.81
Window AC	Capacity	1465 W	1465 W	Autosize
	Max air flow rate	0.0611 m^3/s	0.0611 m^3/s	Autosize
	Rated SEER	13	13	13
	Cooling stage	2	1	1
Heating baseboard	Capacity	Autosize	Autosize	Autosize
	Heating efficiency	0.97	1	1
Transfer Fan	Air flow rate	200cfm (0.0944 m^3/s)	200cfm (0.0944 m^3/s), 151 W	200cfm (0.0944 m^3/s), 151 W

The variables described in Table 5 provide details for the parametric analysis conducted in this study. This diversity allows utilities and other researchers to pick and choose which modeling results apply to their housing stock and extrapolate potential savings estimates accordingly.

Table 8. Prototype characteristics

	Building Area	HVAC System Type	Control Case
Prototype #1	1493 ft^2	DHP with Zonal electrical resistance Heating and window AC	Baseline 1(Both DHP and zonal electric heaters/window ACs set to same set point. Nothing but DHP in living room)
			Bedroom Setback vs B1
			Transfer Fans (Fans installed above bedroom doors to circulate air) vs B1
			Complex Schedule vs B1
		DHP with Central Heating and Cooling	Baseline1(Both thermostats in zone 1, set to the same set point)
			Baseline 2(Central Only)
			Fan Only vs B2 (Central Only)
			Baseline 3 (DHP sensor in living room, Central system sensor in master bedroom, can be set to different set points)
			Central System Offset vs B3
			Stages (1st stage: DHP only. 2nd stage: both DHP and central system on at same time) vs B3

[4] This was a simpler model than the actual heat pump, however, the results of this assumption provides conservative energy saving estimates.

	Building Area	HVAC System Type	Control Case
			Complex Schedule vs B3
Prototype #2	2346 ft^2	DHP with Zonal Heating and Cooling	Baseline 1(Dual Use Baseline)
			Bedroom Setback vs B1
			Transfer Fans vs B1
			Complex Schedule vs B1
		DHP with Central Heating and Cooling	Baseline 1
			Baseline 2(Central Only)
			Fan Only vs B2
			Baseline 3
			Central System Offset vs B3
			Stages vs B3
			Complex Schedule vs B3

Detailed results for the U.S., New York and California are provided in Chen, et al. (2020). An example of the modeling results for New York are displayed in Tables 7 and 8.

Table 9. Estimated energy use and savings in New York for CZ4Moist (DHP with Central System)

Control Scenarios	Heating (kwh)	Cooling (kWh)	Fans (kWh)	HVAC Energy Usage (kWh)	HVAC Energy Saving %[5]
Building Size A: 1493 ft2					
Baseline 1 (Dual)	1436	3456	1153	6044	
Baseline 2 (Central Only)	3378	3525	1147	8050	33%
Fan Only vs B2 (Central Only)	886	2828	2942	6656	-17%[6]
Baseline 3	3933	3642	1189	8764	
Central System Offset vs B3	1992	3128	694	5814	-34%
Stages vs B3	2714	3333	892	6939	-21%
Complex Schedule vs B3	1589	2572	406	4567	-48%
Building Size B: 2346 ft2					
Baseline 1 (Dual)	2475	4517	1558	8550	
Baseline 2 (Central Only)	6639	4678	1564	12881	51%
Fan Only vs B2 (Central Only)	1828	3575	3814	9217	-28%
Baseline 3[7]	8514	4964	1650	15128	
Central System Offset vs B3	4425	4167	1011	9603	-37%
Stages vs B3	5892	4464	1239	11594	-23%
Complex Schedule vs B3	3400	3383	600	7383	-51%

[5] Compared to Baseline 1
[6] Negative numbers in this case indicate savings compared to Baseline 1
[7] Baseline 3 represents the baseline where the DHP is set to the same temperature as the central system, but the central system thermostat is located in the master bedroom.

Table 10. Estimated energy use and savings in New York for CZ6Moist (DHP with Central System)

Control Scenarios	Heating (kwh)	Cooling (kWh)	Fans (kWh)	HVAC Energy Usage (kWh)	HVAC Energy Saving %
Building Size A: 1493 ft2					
Baseline 1 (Dual)	2519	2586	1289	6394	
Baseline 2 (Central Only)	5367	2622	1261	9250	45%
Fan Only vs B2 (Central Only)	1867	2108	3008	6983	-25%
Baseline 3	6297	2714	1319	10331	
Central System Offset vs B3	3786	2269	828	6883	-33%
Stages vs B3	4861	2433	1019	8314	-20%
Complex Schedule vs B3	3136	1919	483	5539	-46%
Building Size B: 2346 ft2					
Baseline 1 (Dual)	4428	3306	1747	9481	
Baseline 2 (Central Only)	10253	3419	1719	15392	62%
Fan Only vs B2 (Central Only)	3789	2608	3842	10239	-33%
Baseline 3	12989	3689	1833	18511	
Central System Offset vs B3	8117	2961	1197	12275	-34%
Stages vs B3	9936	3233	1417	14586	-21%
Complex Schedule vs B3	6181	2481	697	9358	-49%

Conclusions

Considering all of the results presented above, and many discussions between the three team leads represented in this paper, the most energy saving and comfortable control solution that was tested, and is repeatable for homeowners appears to be the central system offset solution, where the central or zonal system is set back (lower in heating season or higher in cooling season). The implementation of that measure could be done with either a fully integrated system (tending to need a contractor to install it, and therefore relatively expensive), or with lower-cost set of controls that can be connected through platforms like If This Then That (IFTTT). Different utilities seem to strongly prefer one of these two control strategies for the same result. The fully integrated systems available on the Mass Save list, are relatively expensive (~$2,000 including installation), but inherently more reliable. The use of IFTTT to connect certain DHP and central controllers is relatively inexpensive (~$400 including do-it-yourself installation), but this process is relatively error prone.

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