Evaluation of Mini-Split Heat Pumps as Supplemental and Full System Retrofits in a Hot Humid Climate

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ABSTRACT

In the Phased Deep Retrofit Project, 53 Florida homes have been monitored for a three-year period with detailed sub-metered data on heat pump energy use as well as temperatures and interior humidity conditions. High-efficiency 25.5 SEER, 12 HSPF, 1-ton, supplemental, inverter-driven ductless mini-split heat pumps (MSHP) were installed in the main living area of ten central Florida homes with the goal of reducing space heating and cooling energy by decreasing runtime of the less efficient, existing central system. Two additional homes received high-efficiency, ductless heat pumps as complete central system replacements – a single ducted unit and a multi-split design.

The supplemental MSHP installations showed median energy savings of 33% (6.7 kWh/day) for space cooling and 59% (6.5 kWh/day) for heating. A large added consumer benefit is a redundant heating and cooling system. Two additional homes that received complete high-efficiency replacements, abandoning the central system, exhibited cooling energy use savings of 37% (7.8 kWh/day) and 29% (3.5 kWh/day). While significant cooling savings were measured, the multi-split installation suffered comfort issues. The mini-split replacement, however, showed superior interior moisture control.

Introduction

Increasing energy efficiency standards and the demand for higher efficiency are growing the popularity of technologies such as min-split heat pumps. According to a meta-study conducted by Faesy et al. (2014), the market for ductless heat pumps is growing 10% - 30% annually. Similarly, according to Marshall and Swan (2014), the U.S. mini-split market has seen a 221 percent growth rate over the prior seven years and a 20% growth rate is expected to continue, citing the introduction of the highly-efficient, inverter-driven compressor as part of the explanation for the growth. Growth projections are supported by high customer-satisfaction, but with most of the research on space heating applications (Faesy et al. 2014, Lubliner et al. 2016).

However, studies report highly-variable MSHP energy savings results (Faesy et al. 2014). In heating-dominated climates MSHPs are typically supplemental retrofit installations, providing the primary source of heating to the areas that are most used (Baylon et al. 2012, Lubliner et al. 2016, Faesy et al. 2014). Research on southern climate MSHP installations where the primarily focus is on cooling is limited. However, sparse data suggests MSHPs are primary installed 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 et al. 2014, Marshall and Swan 2014). MSHP research needs recommended in the Northeast-focused Faesy meta-study (2014) include: more field performance as opposed to laboratory testing, measured performance and savings evaluations in different climates zones, and more sub-metered load shape, energy use, and energy savings information. In a case study evaluating MSHPs as a complete system solution in the hot humid climate, Roth et al. (2013) found comfort issues and recommended that future research with field performance data.

The particular project presented within was intended to provide such gap research identified above. The Phased Deep Retrofit (PDR) project, conducted by the U.S. Department of Energy Building America team— Partnership for Improved Residential Construction (BA-PIRC)— in collaboration with Florida Power & Light (FPL), sought to determine the impacts on annual energy reductions from the installation of advanced residential technologies. Using this platform, researchers investigated impacts of MSHP retrofits to answer questions about energy use savings, peak load shaving, and comfort issues in the hot-humid climate.

Background

Total house power as well as detailed energy end-use data were collected to evaluate energy reductions and the economics of each retrofit at each PDR study home. All of the homes were audited and instrumented during the second half of 2012; shallow retrofits were conducted from March–June 2013. Monitoring of hourly house power and the various end uses was accomplished with a 24-channel data logger as supplemented by portable loggers to take temperature and relative humidity (RH), located near the central system thermostat. (Additional portable loggers were launched to obtain room-by-room comfort data). Hourly power was measured by SiteSage loggers, generally using 50-amp current transformers which have a stated accuracy of ±1% between 10% and 130% of their rated output. Interior temperatures were measured near the thermostat using Onset HOBO U-10-003 portable loggers with a stated accuracy of ±0.95°F for temperature and ±3.5% RH for relative humidities up to 85%.

Evaluation Method

Regression analysis was used to project space conditioning energy savings for each retrofit measure. To estimate pre- and post-retrofit annual space heating and cooling energy use, daily average ambient temperatures were regressed against monitored daily HVAC energy use. In keeping with the statistical analytical concept of parsimony, this study used the simplest model that showed stable and reliable results with strong explanatory power, a linear regression using a single independent variable. Outdoor temperature (in degrees Fahrenheit) was used rather than outdoor temperature minus indoor temperature because of expected behavioral changes with the supplemental or total MSHP replacement. Differences in interior temperature are likely with the MSHP because uniform interior room temperatures do not typically yield the greatest comfort. Brand (1987) found that space conditioning systems that facilitate zoning have significantly lower energy use. When a supplemental or total MSHP is added, it becomes likely that occupants maintain different heating and cooling conditions in different rooms of the home. For each site, the typical meteorological year 3 (TMY3) weather data were applied to the regression coefficients to normalize the savings.

Supplemental Ductless Mini-Split Heat Pump Measure

Ten central Florida project homes received supplemental MSHPs from August 27, 2014–July 23, 2015. The research question was: Can a very efficient ductless mini-split heat pump be added centrally to homes already possessing a conventional central ducted system to reduce the runtime of the lower-efficiency central system.

The equipment chosen for this measure was the 1-ton ductless, inverter-driven Panasonic XE12PKUA, SEER 25.5 Btu/Wh, 12 HSPF. The variable speed units have an Air-Conditioning, Heating, and Refrigeration Institute (AHRI) rated nominal cooling capacity of 11,580 Btu/hr at the 95/80/67 rating condition, ranging from 2,800 to 14,000 Btu/hr, and a heating capacity of 13,800 Btu/hr at 47°F outdoors. As shown in Table 1, homes receiving the supplemental mini-splits were highly varied, with central AC systems of various ages and efficiencies. Duct systems for all central systems were located in the attic space of each home.

Table 1. Supplemental MSHP Site and Existing HVAC Characteristics

Site #	Year Built	Living Area (ft^2)	Year of AHU[a]	Year of Compressor	AC Size (tons)	AC SEER [b]	Heat Pump (HP) or Electric Resistance	HSPF [b]	Duct Leakage (Qn,out)[c]	Duct Leakage Out (CFM)
3	1993	1856	1993	2010	3.5	13	HP	7.5	0.05	100
5	2006	2328	2006	2006	5.0	13	HP	7.5	0.10	234
12	1984	1594	2000	2000	3.0	12	HP	7.8	0.63	1003
16	1982	2231	2002	2014	4.0	13	Resistance		0.07	153
21	1981	1628	2013	2013	3.5	13	Resistance		0.12	188
23	1980	1946	2001	2002	3.5	14	Resistance		0.05	101
24	1986	1978	2010	2010	3.5	15	Resistance		0.09	187
27	1995	2050	2008 Pkg. Unit		5.0	12	Resistance		0.05	107
54	1999	1390	1999	1999	2.5	10	HP	7.5	0.03	49
60	1987	1520	2006	2006	3.0	15.5	Resistance		0.04	56

[a]Air Handling Unit
[b]Some systems were apparently unmatched; stated are manufacturer listed compressor efficiencies.
[c]Duct leakage measured at a test pressure of negative 25 pascals with respect to the outside, divided by the building's conditioned floor area. Site 12 results were projected as test pressures could not be reached.

The supplemental MSHPs were expected to reduce space cooling and heating energy by reducing the runtime of less efficient existing central systems subject to duct losses. However, the configuration with two different systems with potentially competing thermostats serving a single zone added speculation for how this would work out. Moreover, no existing simulation model can provide savings estimates because having two HVAC systems serve the same zone violates limits for hourly calculations.

The indoor fan coil was centrally-located within each home. In most cases, the unit was located as close as possible to the central return grille of the existing system to help with room-to-room distribution of MSHP air when the central unit was operating. At install, the cooling set point of the MSHP was set either 2° or 4°F lower than the central system temperature. Owners were advised against setting the central system fan to run constantly to avoid moist air from compressor coils being brought back into the home and avoid excessive fan energy consumption.

Supplemental MSHP: Results and Discussion

To examine how the supplemental MSHP influenced space cooling and heating energy an evaluation method was applied to the measured data for each installation. The evaluation periods generally spanned about 18 months in total: January 2014 through July 2015 for the late summer 2014 installations and summer 2014 through January 2016 for the early summer 2015 installations. Evaluation periods varied according to: installation date, other retrofit measures, and other significant changes, such as a change in occupancy. Energy savings results were normalized to TMY3. Tables 2 and 3 show the cooling and heating results from the regressions along with the hourly-logged interior temperature (Int T) and relative humidity (RH) (for cooling), as measured nearby the thermostat, before and after the MSHP retrofit. Space cooling energy savings were large, with a median of 33%, 2,007 kWh/year, or about 6.7 kWh/day. The median daily space heating savings were 59%, 390 kWh/year or about 6.5 kWh/day.

Table 2. TMY3-Normalized Cooling Energy Use and Savings from the Supplemental MSHPs

Site #	Pre-Cooling (kWh/yr)	Post-Cooling (kWh/yr)	Savings (kWh/yr)	Savings (%)	Pre-Int T (°F)	Post-Int T (°F)	Δ T	Pre-RH (%)	Post-RH (%)	Δ RH
3	8,049	5,419	2,631	33	75.0	75.0	0.0	51.2	54.1	2.9
5	15,586	10,006	5,580	36	75.7	76.0	0.3	49.4	50.1	0.6
12[a]	7,571	6,024	1,547	20						
16	7,014	5,344	1,670	24	76.9	76.2	-0.7	56.7	55.3	-1.5
21	4,970	2,700	2,270	46	79.5	80.2	0.7	58.5	60.1	1.7
23	9,820	6,379	3,441	35	74.8	72.4	-2.4	45.3	45.0	-0.3
24	7,321	7,196	125	2	74.8	73.1	-1.7	54.8	48.3	-6.5
27	13,037	8,018	5,019	39	75.1	75.0	-0.1	45.4	46.2	0.7
54	8,112	6,426	1,686	21	76.4	75.5	-0.8	46.4	51.6	5.2
60	5,321	3,577	1,745	33	76.1	76.7	0.6	52.4	50.7	-1.6
Average	8,680	6,109	2,571	30	76.0	75.6	-0.5	51.0	50.9	0.2
Std. Dev.			1,674							
Median			2,007	33			-0.1			0.6

Table 3. TMY3-Normalzied Heating Energy Use and Savings from the Supplemental MSHPs

Site #	Pre-Heating (kWh/yr)	Post-Heating (kWh/yr)	Savings (kWh/yr)	Savings (%)	Pre-Int T (°F)	Post-Int T (°F)	Δ T
3	115	94	22	19	68.7	70.6	2.0
5	734	309	424	58	73.2	73.0	-0.3
12[a]	235	218	18	8			
16	476	86	390	82	68.4	70.5	2.1
21	585	103	482	82	73.8	73.2	-0.6
23	1,516	592	925	61	73.9	72.9	-1.0
24	361	206	155	43	68.9	68.3	-0.6
27	2,627	1,082	1,544	59	73.8	75.1	1.3
54[b]							
60	427	111	316	74	73.0	73.1	0.1
Average	786	311	475	60	71.7	72.1	0.4
Std. Dev.			487				
Median			390	59			-0.1

[b]Site had no pre-retrofit heating to measure.

Examining the sites as a group, cooling season interior temperature and RH were relatively similar between pre- and post- periods, on average, and with dew points averaging 68.3°F pre and 69.2°F post. On average, no moisture removal advantage of the supplemental MSHP was apparent. The heating season interior temperature is also essentially unchanged between periods, on average, however there were some increases. Cooling season ambient temperature was typically slightly cooler, averaging 0.4°F lower post-retrofit (76.9°F vs. 76.5°F).

However, there were significant variations for some homes. For instance, the innovative configuration showed a large improvement to interior temperature and RH at Site 24 – reductions of 1.7°F and 6.5%, respectively, where the average dew point exceeded 69°F both pre-and post-retrofit. The impact on savings can be large. For example, each 1°F reduction in interior temperature below 80°F, FSEC has measured between a 9% and 14% change in air conditioner power (Barkaszi and Parker 1995). Site 24 also showed the lowest cooling energy savings – 2%. Assuming an 11.5% increase in energy use for every 1°F of post-retrofit take-back, cooling energy savings would have been about 18% without the take-back.

The average percent space heating energy savings achieved by the supplemental MSHPs were greater than that for cooling. This occurs because Sites 16, 21, 23, 24, 27, and 60 had electric resistance heating (the other four sites had heat pumps). The mini-splits with the much more efficient, inverter-driven heat pump technology provided most of the heating capacity which eliminated or reduced auxiliary strip heat of central systems. Figure 1 shows the times series data where electric resistance strip heat is highly visible, as is the reduction to the space cooling in summer and the very low power of the mini-split system for Site 60.

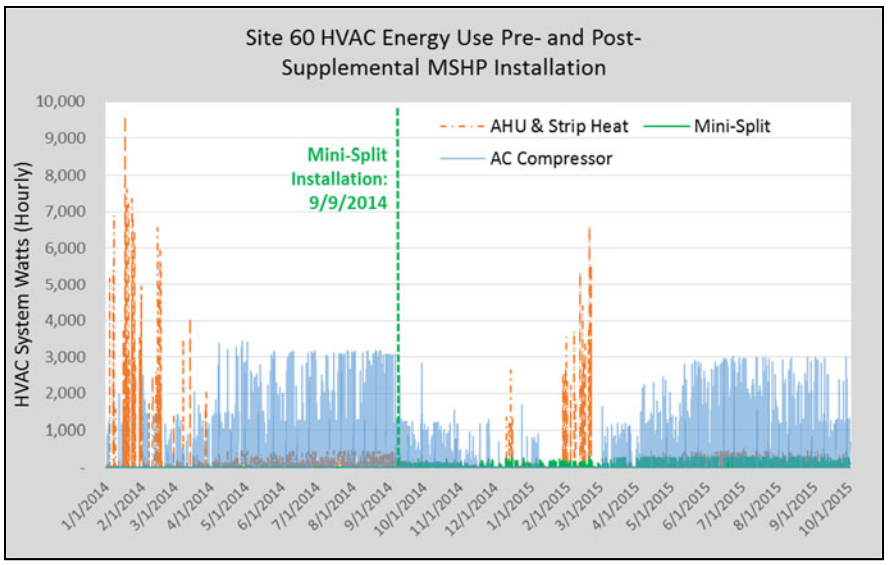

Figure 1. Time series data showing heating, ventilating, and air-conditioning energy use by air-conditioner compressor, air handler unit and strip heat, and supplemental mini-split for Site 60.

The projected HVAC annual energy savings from the supplemental MSHP measure for all ten sites averaged 34% or 2,357 kWh/year. Results have been normalized using population-weighted TMY3 weather stations to represent average savings estimates for the FPL service territory. Table 4 summarizes the projected annual savings.

Table 4. TMY3-Normalzed Annual Cooling and Heating Energy Use and Savings from the Supplemental Mini-Splits

Site #	Pre- (kWh/yr)	Post- (kWh/yr)	Savings (kWh/yr)	Savings (%)
3	8,165	5,513	2,652	33%
5	16,320	10,315	6,004	37%
12	7,807	6,242	1,565	20%
16	7,490	5,430	2,060	28%
21	5,555	2,803	2,752	50%
23	11,337	6,971	4,366	39%
24	7,682	7,402	280	4%
27	15,664	9,100	6,563	42%
54	8,112	6,426	1,686	21%
60	5,748	3,687	2,061	36%
Average	9,388	6,389	2,999	32%
Std. Dev.			2,020	
Median			2,357	34%

The average full retail cost for equipment, materials, and labor for each of the ten supplemental MSHP installations was about $3,900, in line with $3,500 - $4,000 installed costs reported by Faesy et al (2014) for 1-ton units. The median annual HVAC energy savings translates into about $285 saved per year (2,375 kWh/year * 0.12/kWh), which yields a simple payback in about 14 years and an annual rate of return of 7.3%. In a mature market, economics are likely to improve with equipment and labor cost reductions—particularly as crews become more familiar with the relatively simple job of installing MSHPs. This cost analysis does not consider one notable benefit to the consumer—the redundant heating and cooling system for the home, which is highly desirable given the inconvenience of inevitable and unpredictable failure of central AC systems, some of which may take a few days to repair.

In order to evaluate the supplemental MSHPs' influence during peak summer and winter hours, HVAC power demand at the utility coincident peak hours in 2014 were compared to those of 2015. Figure 2 compares the average HVAC demand of the ten supplemental MSHP sites for the summer peak, showing a large demand reduction of 0.50 kWh or 16%.[1] The winter peak evaluation is limited to the six supplemental MSHPs installed in 2014. Figure 3 compares the

[1] Utility summer peak was July 28 in 2014 (pre-retrofit); 2015 utility summer peak post retrofit was August 20.(Z. Morales, Florida Power & Light Co., pers. comm., January 21, 2016). Utility winter peak was January 23, 2014 (pre-retrofit) and February 20, 2015 (post-retrofit).

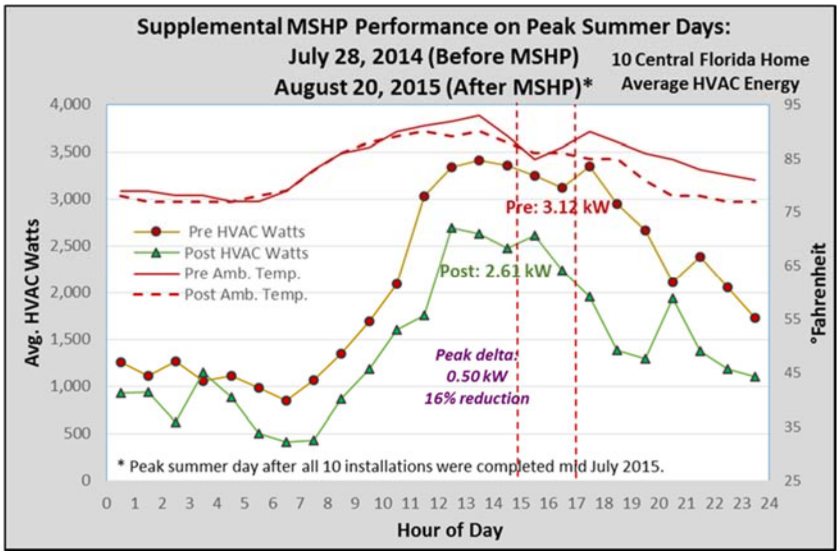

Figure 2. HVAC demand on FPL system peak summer day - 2014 vs. 2015.

average HVAC demand at these sites, which shows a very large demand reduction of 2.06 kW or 56% between 7 and 8 a.m.

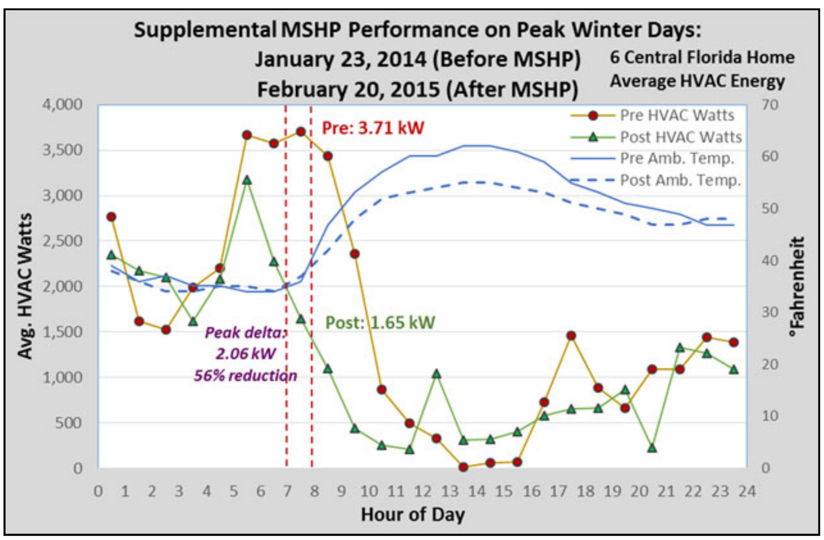

Figure 3. HVAC demand on FPL system peak winter day - 2014 vs. 2015.

In summary, the median annual HVAC energy reductions for the supplemental MSHP were impressive at 34%, with utility demand reductions of the supplemental mini-split also very large in both summer and winter, for the small sample of ten and six sites, respectively. Reductions to long-term average interior RH were sometimes observed, albeit inconsistently.

Complete System Replacement with Mini and Multi-Split Heat Pumps

Another important objective of the PDR project was to evaluate a high-efficiency, single and multi-unit inverter-driven heat pumps as a full replacement to the existing central system. This was conducted at two sites to investigate possible space cooling and heating energy use reductions when a traditional-type central system is replaced. Testing before and after allowed detailed insight into impacts on energy use and comfort. Two different replacement schemes were tested to allow evaluation of contrasting solutions. The first design involved a multi-split with a single condenser and two fan coils – a ductless unit to condition the main living area, and a ducted component to condition the rooms remote from the main living space – referred to as "Multi-Split Heat Pump." The second design for central system replacement consisted of one MSHP with interior ducts to condition the whole house, denoted as "Ducted MSHP."

Multi-Split Heat Pump: Materials and Methods

Site 11, the home for the multi-split design, is a three-person occupancy, single-story, three-bedroom, two-bathroom home with 1,672 ft^2 of living space located in Cocoa Beach, Florida. The existing system was a 12.0 SEER, 7.5 HSPF rated, 3-ton heat pump. A single, centrally-located return feeds into the interior-located fan coil. Supply air is distributed via ducts to the bedrooms and bathrooms through the unvented attic, and to the remainder of the building inside a chase. The flex ducts (~R-4 hrft^2-F/Btu) are poorly sealed (Qn,out = 0.13).

The retrofit consisted of a single 3-ton compressor tied to both a 1.5-ton wall-mounted fan coil installed in the main living area and a 1-ton ceiling-mounted fan coil in the hallway of the home. A Carrier model set (manufactured by Toshiba) was chosen – the 38MGQF36 variable speed condensing unit, the 40MAQB18B wall-mount, and the 40MBQB12D ceiling-mount. The performance rating on the system varies from a high of 18 SEER, 10.0 HSPF with non-ducted units to 15 SEER, 9.2 HSPF with ducted units. The rating for use of a combination of ducted and non-ducted units is 16.5 SEER, 9.7 HSPF. The system has a nominal AHRI rated cooling capacity of 35,000 Btu/hr at an outdoor temperature of 95°F, ranging from 9,500-37,000 Btu/hr, and a heating capacity of 36,000 Btu/hr at an outdoor temperature of 47°F.

The multi-split heat pump installation took place between July 1 and 8, 2015. The wall-mounted fan coil was installed in the dining area on an exterior wall of the house for the system to service the kitchen, dining room, living room, and Florida room. The ceiling-mounted fan coil was installed at the far end of the hallway to service the bedrooms, office, and second bathroom. The dropped ceiling above the hallway provided the best location to house the fan coil and run very short supply ducts through the knee walls to the adjacent bedrooms with single assembly ceilings, although configuration space was limited. While initial post-retrofit airflow and duct leakage test results were poor, the mechanical contractor revisited the installation, resealing duct work and sealing the return plenum with satisfactory results. The total cost for the installation was $8,100.

Multi-Split Heat Pump: Results and Discussion

The occupants expressed comfort issues from the completed multi-split system.[2] Temperature imbalances across rooms were experienced during the height of the cooling season, with the office becoming too cool while the master bedroom was often too warm. Figure 4 shows the hourly average daily temperature profile for four rooms during two summer weeks. The

[2] The homeowner reaction at the multi-split replacement site was quite the different than at the ducted mini-split site - discussed in the next section - where occupants were delighted with improved comfort and performance.

dining room in green is serviced by the unducted, 1.5-ton wall-mounted fan coil. Temperatures for the bedrooms and office are in red, orange and blue.

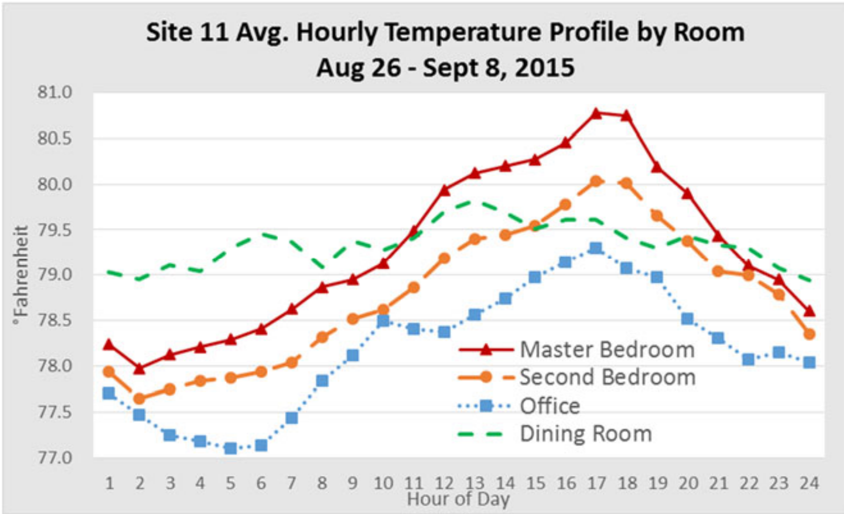

Figure 4. Average hourly temperature profile of four interior locations.

The plot displays that while the dining area maintains a level temperature of 79° to 80°F throughout the day, the temperatures in the three rooms served by the ducted ceiling-mounted fan coil fluctuated by as much as 2°F each day and across rooms. The homeowner reported frequently altering the ceiling-mounted unit's thermostat set point and restricting airflow to the office (often too cold) in attempt to achieve comfort. Moreover, examination of the relative humidity in the rooms serviced by the ducted ceiling-mount unit revealed higher and more variable RH post-retrofit. Figure 5 displays changes in RH in the second bedroom. The post-retrofit RH frequently exceeds 60% with high variability. Given the very high air leakage of the house, indoor RH may have exceeded 60% more frequently pre-retrofit than is indicated by the snapshot in Figure 5.

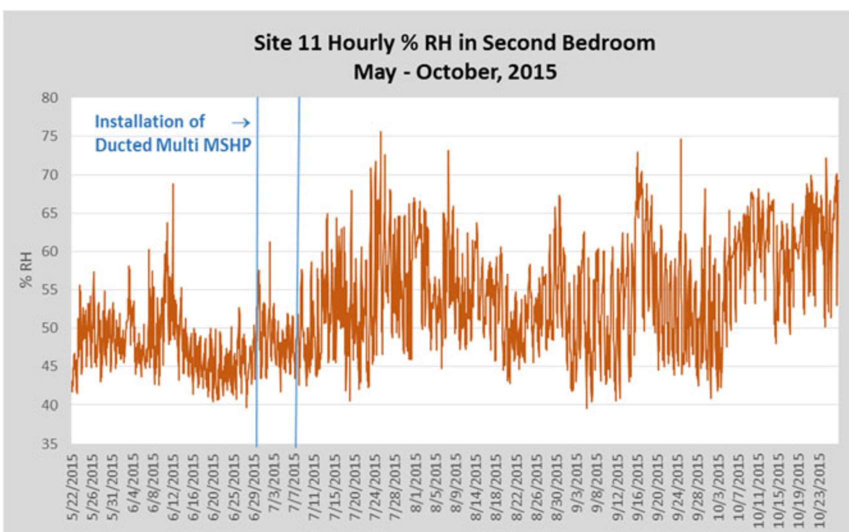

Figure 5. Hourly RH in the second bedroom, pre- and post-retrofit.

After learning about the interior temperature and humidity issues, a site visit with Carrier technicians uncovered two possible contributing problems: 1) sensing location issues (whether sensing temperature at the fan coil which is located in a semi-conditioned attic buffer space, or at the thermostat located in the hall – an area only indirectly conditioned by the unit) and 2) a temperature response lag. (Upon start up or set point change, the delta between set point and the temperature that will trigger the fan coil system to cycle off is about 4°F). Scarce monitored data exists regarding the ability of multi-split systems to effectively dehumidify homes in humid climates.[3] The room temperature and RH was specifically examined before and after the duct repair indicating this was not the likely source of the performance issue.

While the additional runtime of an inverter-driven system may provide enhanced latent removal, it is restricted in the multi-split case by the maximum "turn-down" ratio – the width of the operational range, defined as the ratio from maximum to minimum capacity. For example, a 3-ton single-unit can typically provide about 1-ton (33%) of the maximum outdoor compressor capacity, while a multi-unit design consisting of a 2-ton and a 1-ton unit is capable of "turning-down" to 4,000 Btu/hr (33% of the smallest unit). Thus, a multi-split system with a single outdoor unit is less capable of operating during low sensible load conditions compared to if zoning were accomplished by two independent mini-split systems delivering the same total capacity. This is a known issue that the industry is working to solve.

While these points may be related to the comfort issues at Site 11, RH only appeared to be a problem in the rooms serviced by the ceiling mount, and not the main living area. (See Table 5 for the post-retrofit change in the main living area RH). This again points to a specific limitation in the multi-split arrangement where the sizing of the single outdoor compressor may be critical to the potential degree of control at low cooling loads.

A graphical display of the average daily space cooling energy, interior and exterior temperature, and interior RH spanning a portion of the analyzed pre- and post-retrofit periods are provide in Figure 6. The central system (condenser and AHU in red) operated until July 10, 2015 and the multi-split system (green) was operational on July 8, 2015. Contractor work began July 1st and was essentially completed July 10th. Exterior temperature is in orange, interior temperature in blue, and RH in purple. Note the RH in this plot was taken from the main living area sensor. A large reduction in HVAC energy was observed, while interior temperature appears elevated post-retrofit. There was large variation in relative humidity pre and post.

[3] http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-23017.pdf

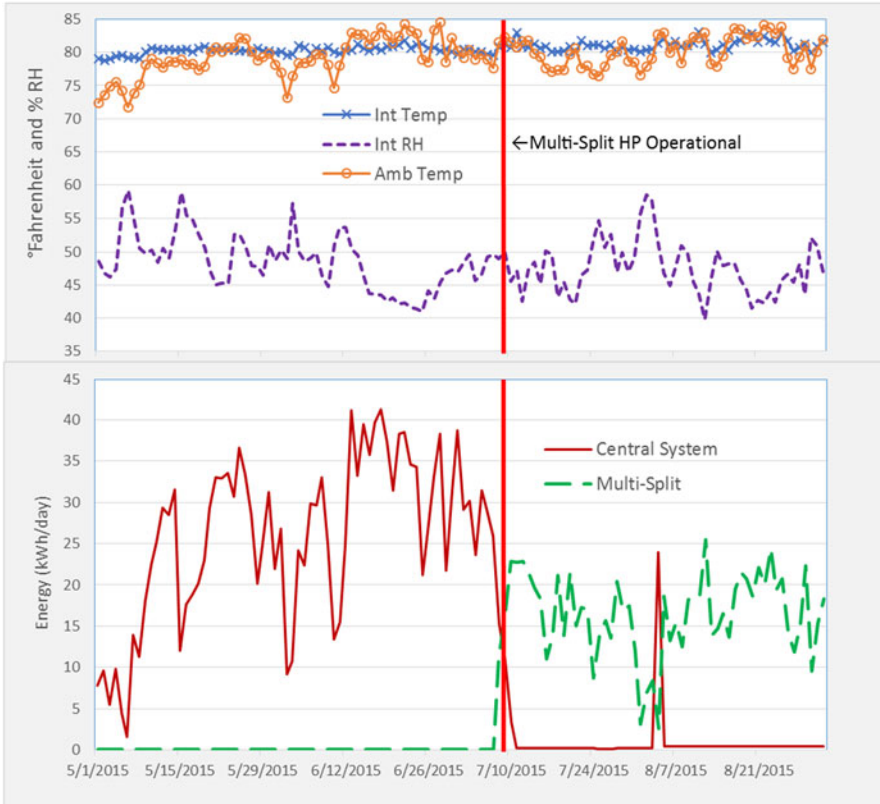

Figure 6. Daily average HVAC energy, indoor & outdoor conditions: May 1-Aug 31, 2015.

Because the homeowners had a highly-reflective white metal roof installed a few months after the multi-split, a limited evaluation period was necessary to avoid this confounding retrofit measure. The pre-retrofit period was also bound to exclude data after the installation of a smart thermostat. With the abbreviated observation time, weather conditions were matched between evaluation periods. Each period consisted of approximately three months of data. The ambient conditions were similar between periods – the average exterior temperature was slightly cooler post-retrofit (80.5°F pre vs. 79.9°F post) and the average dew point was slightly higher post-retrofit (73.1°F pre vs. 73.7°F post). Predicted cooling and heating energy savings and interior conditions are summarized in Table 5.

Table 5. Multi-Split Heat Pump Space Conditioning Energy Savings

	Pre-	Post-	Savings		Bal. T	Interior Temp. (°F)			Interior RH (%)		
	kWh /yr	kWh /yr	kWh /yr	%	(°F)	Pre	Post	Δ	Pre	Post	Δ
Cooling	6,010	3,759	2,250	37	67	80.4	80.9	0.5	51.2	48.8	-2.4
Heating	459	46	-5	-1	67	72.8	76.9	4.1	n/a	n/a	n/a
Annual	6,469	4,224	2,245	35							

Estimated space cooling energy savings was 37%, 2,250 kWh/year or 7.8 kWh/day, while the home is being kept slightly warmer post-retrofit - 0.5°F higher than pre-retrofit. Meanwhile, the average indoor RH in the main living area is 2.4% lower post-retrofit than pre-retrofit, amid similar pre- and post-retrofit ambient conditions. While the main living space RH decreased, it is important not to overlook increased RH in the rooms served by the ceiling-mounted fan coil.

Evaluating the multi-split heat pump's impact on a utility peak summer day, HVAC power demand at the peak hour in 2014 was compared to 2015 showing a reduction of 0.24 kWh (11%). Space heating energy savings were slightly negative (1% or 5 kWh/year). Occupant take-back was the likely explanation: selected post-retrofit main area temperature was about 4°F warmer than during the pre-retrofit heating period.

The projected energy savings from the multi-split heat pump are impressive at 35% or 2,245 kWh/year. Still, with a cost of $8,100, the economics are only attractive at time of replacement. Also, identified comfort issues arising from this design need to be resolved before broad recommendation. A two-compressor design may solve comfort issues, but at greater cost.

Ducted Mini-Split Heat Pump: Materials and Methods

The subject site is a two-person occupancy, single-story, ranch-style, three bedroom, one bathroom home with 875 ft^2 of living space located in Cocoa Beach, Florida. The existing air conditioner at Site 61 is a 13.5 SEER rated, 2.5-ton system with electric resistance heat. A single, centrally-located, unducted return feeds into the interior-located fan coil. Supply air is distributed through the vented attic in insulated R-4.2 rigid ducts with poor airtightness (Qn,out = 0.14).

The retrofit abandoned the leaky attic ducts and associated conductive losses. Contractor suggested sizing (99% of design day) indicated a 1.5-ton unit. A single 20.0 SEER, 11.5 HSPF, 1-ton, ceiling-mounted MSHP was installed in the hallway of the subject home, with short duct runs below the ceiling plane distributing conditioned air to the main rooms of the home. A Fujitsu model set was chosen – the ARU12RLF fan coil fan coil unit and matched AOU12RLFC condensing unit with variable refrigerant flow. The system has a nominal AHRI rated cooling capacity of 12,000 Btu/hr at 95°F, and a heating capacity of 13,500 Btu/hr at 47°F.

The installation of the ducted MSHP began June 18, 2015 and spanned three weeks including finish carpentry work. The new ductwork and fan coil was installed in the home's centrally-located hallway, inside conditioned space below the ceiling plain. All three bedroom doors are accessible from the approximately 12-foot long hallway. Supply air is distributed to all three bedrooms, the living room, and the kitchen, with each room designed to receive between about 50 and 100 CFM. The total cost of the ducted MSHP installation was $9,100.

Ducted Mini-Split Heat Pump: Results and Discussion

The ducted mini-spit design significantly improved latent control and provided large energy savings. Much of this improvement was likely due to the abandonment of leaky attic ducts and use of an interior duct system. Figure 7 plots the RH for all rooms and exterior dew point before and after the retrofit. Though RH remains variable from pre- to post-retrofit, RH in all rooms is sharply reduced. In fact, the average RH for all rooms during this snapshot was 55% pre-retrofit and 45% post-retrofit while the average ambient dew point was higher between these same periods. Follow-up conversations with the homeowner indicated they are very pleased with the interior comfort from the new system.

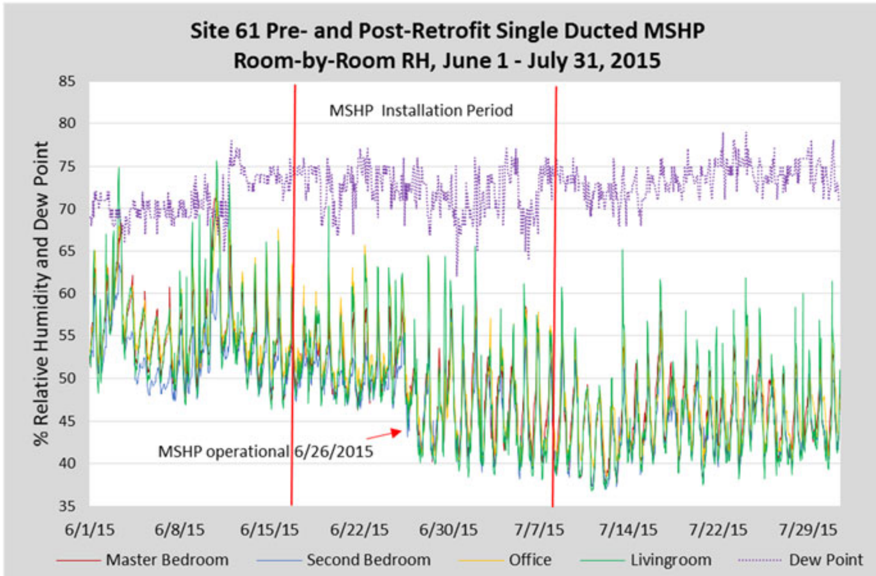

Figure 7. Pre- and post-retrofit room-by-room relative humidity.

Figure 8 displays daily space cooling energy use and interior and outdoor conditions. System operation (central system in red; ducted MSHP in green) was switched on June 26, 2015. Exterior temperature is in orange, interior temperature in blue, and RH in purple. Post-retrofit space cooling energy savings are obvious, as is a reduction in interior RH.

Space conditioning energy savings were evaluated using a pre-retrofit evaluation period of July 2014 until installation in June 2015 and a post-retrofit evaluation period from July 2015 through early January 2016. Table 6 summarizes energy savings and interior conditions. Predicted space cooling energy savings is 29%, 948 kWh/year or 3.5 kWh/day, while on average the home was about 1°F cooler and RH was 5.3% lower post-retrofit over the pre-retrofit conditions. While the post-retrofit average exterior temperature was similar between evaluation periods (77.9°F pre vs. 78.3°F post), the post-retrofit period was moister with an average dew point 1.6°F higher (69.5°F pre vs. 71.1°F post).

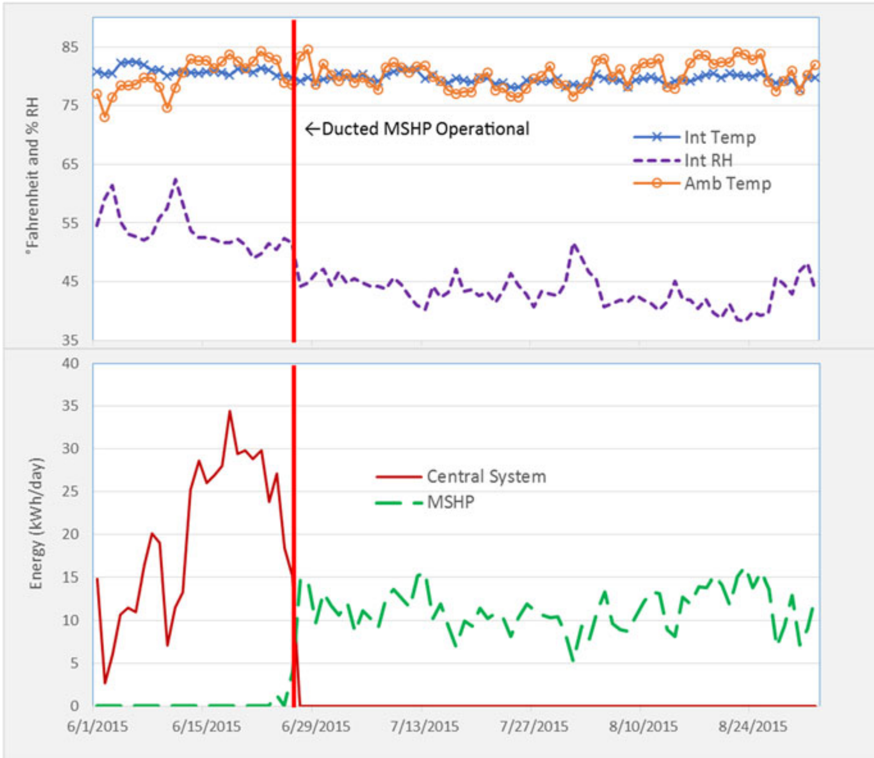

Figure 8. Site 61 avg HVAC energy, indoor &outdoor conditions: June 1-Aug 31, 2015.

Table 6. Ducted MSHP Space Conditioning Energy Savings

	Pre-kWh/yr	Post-kWh/yr	Savings kWh/yr	%	Bal. T (°F)	Interior Temp. (°F) Pre	Post	Δ	Interior RH (%) Pre	Post	Δ
Cooling	3,248	2,300	948	29	70	79.1	78.2	-0.9	62.4	57.1	-5.3
Heating	791	190	601	76	70	72.0	73.1	1.1	n/a	n/a	n/a
Annual	4,038	2,490	1,548	38							

Greater savings would likely have been achieved without the apparent, (and occupant acknowledged) take-back behavior. However, it is clear from homeowner comments that the abandoned central system was unable to satisfy comfort needs. Space heating energy savings is large, which is as expected given that the pre-retrofit heating was electric resistance. The heating savings of 76%, 601 kWh/year or 6.7 kWh/day also includes some behavioral take-back as the occupants preferred a warmer post-retrofit period by about 1°F. However, a portion of the post-retrofit heating evaluation period is post attic insulation.

Observed space conditioning energy savings from the ducted MSHP was impressive at 38% or 1,548 kWh/year. However, with a cost of $9,100, the economics are only attractive if exercised at the end of the existing system’s life. Assuming incremental costs over a new central system are ~$3,000, the savings combined with the markedly improved interior conditions make the ducted MSHP an attractive option.

An evaluation of the ducted MSHP on utility peak summer hour showed HVAC power demand was reduced was 0.70 kWh or 41% between 2014 and 2015. All things equal, this appears a superior option to the multi-split strategy—at least until latent removal issues are addressed. However, the findings here are based on single case studies and further field evaluation is critically needed.

Both retrofits were expensive, but would be competitive if replacing a conventional unitary AC system at burn-out. To consider the ducted mini-split approach, however, it must be noted that in a full-sized house, two to three ducted mini-splits would be needed, depending upon room layout, to achieve similar results. Still, the potential to provide excellent energy savings with improved interior RH control could be a large advantage.

Conclusions

The Phased Deep Retrofit project in Florida evaluated high-efficiency ductless mini-split heat pumps. Results for the novel supplemental MSHP configuration suggest cooling energy use savings of 33% (6.7 kWh/day), and heating energy use savings of 59% (6.5 kWh/day). The daily heating energy percent savings was significantly greater than that for cooling in the six homes with electric resistance central heating. Electrical demand reductions during utility peak system hour were 16% for summer and 56% for winter. With similar pre-and post-retrofit weather conditions, the supplemental MSHP showed similar moisture control characteristics pre and post. Economics using median savings and a current installation price of about $3,900 are potentially attractive, with a suggested payback of about 14 years and 7.3% annual rate of return. As the MSHP market matures and installation costs fall, the economics will further improve. A redundant heating and cooling system is a large added benefit to the consumer —highly desirable given the 7-10% annual failure rate of central AC systems (Welch and Rogers 2010).

An additional central system replacement involved installation of a multi-split with one condenser and two fan coils – a ductless unit to condition the main living area, and a ducted component to condition the rooms isolated from the main living zone. Cooling energy savings were excellent at 37% (7.8 kWh/day) with electric demand reductions during utility peak summer system hour of 11%. With an installed cost of $8,100, the economics are attractive at the time of old system replacement. Nevertheless, this installation created comfort issues.

The design for a second complete HAVC solution consisted of one MSHP ducted to condition the whole house—a modest, compact single-story design. Space conditioning savings totaled 38% (1,548 kWh/year), comprising of 29% (3.5 kWh/day) for cooling, and 76% (6.7 kWh/day) for heating. Large reductions were seen in relative humidity (5.3%) during the cooling season amid slightly higher ambient dew point conditions. Electrical demand reductions during peak summer system hour were 41%. With an installation price of $9,100, economics are attractive if installed upon existing system failure.

In two cases, the performance of a mini- and a multi-split system were compared to that of a standard conventional ducted unitary system at the same site in the hot-humid climate. Both systems showed impressive cooling energy savings, however, the multi-split system showed problems with controlling indoor humidity and zone temperatures. The ducted mini-split approach showed significantly reduced indoor relative humidity. However, a split-plan house would require installation of added ducted MSPH units, greatly increasing cost.

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