The Next New Thing -- Is it really that good?

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ABSTRACT

What is the latest thing in HVAC? Variable Speed (VS) systems are causing quite a stir. The group is a mix of mini-split and multi-split heat pumps and air conditioners (M-Splits). Some of these units sport rated SEERs over 30, more than twice the Federal minimum standard -- generating EXCITMENT. Is the enthusiasm warranted or should evaluators and policy makers be cautious of embracing the rated efficiencies of these units as real? This project reviews literature, laboratory data and the actual efficiencies of these units over entire heating and cooling seasons.

The Central Valley Research Home (CVRH) project provides in-situ monitoring comparisons of three different brands of M-splits to more conventional (reference) systems. Using a flip/flop method, each M-Split was installed in an existing home and operated on the same thermostat schedule as the reference system. Occupant interactions can disturb the results so this study used robots (a standardized schedule of internal gains) in the unoccupied homes. The heating and cooling results for the reference and M-Split systems provide direct comparison between rated efficiencies and actual efficiencies of these machines. The potential improvement in efficiency was not realized in all but one of the cases in the three test homes when the units were tested as installed by the contractors. Rather than saving energy the three tested VS units used more than the reference units they were tested against. In one case the VS unit used over twice the cooling energy of the reference unit.

Introduction

The Central Valley Research Homes (CVRH) project established experimental conditions in four homes of different vintages in Stockton, California. This project has multiple purposes. One of the primary purposes is to provide a test bed for emerging technologies. One of the emerging technologies tested is alternative distribution systems for heating and cooling. A variety of alternative systems were tested in the three years of the project. This paper summarizes the summer (cooling) and winter (heating) performances of mini-split and multi-split heat pumps installed in these homes.

Variable Speed systems come in a wide mixture of designs. There are ducted systems designed either for short low restriction ducts or for more conventional duct systems. There are non-ducted systems that deliver the heating or cooling directly to the space. In both ducted and non-ducted there are mini-splits, which use a single outside unit for the single indoor unit (head) and there are multi-split units that use two or more indoor heads for a single outdoor unit. Figure 1 shows these configurations.

Figure 1. Mini split non-ducted, Mini split ducted, and Multi split Configurations

Literature Review

Southard, Liu, & Stitler (2014) reported on the performance of a multi-split (VRF-Variable Refrigerant Flow) system and a ground source heat pump installed on the administration building at the ASHRAE headquarters. Their conclusion stated: "the average system heating COP of the VRF system was 2.0±0.1 and the average system cooling EER was 8.5±0.4." The report continues: "The heating and cooling efficiencies of both systems are lower than that listed in the manufacturer's catalogue data, particularly for the VRF system."

In 2011 and 2014 Ecotope reported on the Northwest Ductless Heat Pump Pilot Project. The project used Ductless Heat Pumps (DHP) to supplement existing zonal electric resistance heating systems. Extensive laboratory testing was performed on two units from two different manufacturers. The project included 3,899 installations and field testing in addition to the laboratory testing (Ecotope 2011, Ecotope 2014). Both the reports contained the following conclusions:

- The lab data demonstrates the high performance of both models.
- Lab and field COP measurements show good agreement.
- The current HSPF and SEER ratings are not well suited to DHPs.

With the exception of concern with respect to HSPF and SEER ratings, these conclusions present a supportive picture of the tested DHPs. Within the reports, other items are noted:

The laboratory data and field data for one of the tested models show steady state heating COPs consistently less than the manufacturer's specification except at low speed and 57ºF outdoor temperature (Ecotope 2011, 17).

- For both lab-tested units the airflow in heating was consistently lower than the manufacturers' listed values. The discrepancy varied from 6% to 16% and averaged 9% low (ibid, 10).
- One of the advantages of a variable speed machine is that it can adjust to the appropriate (lower) speed to increase efficiency and reduce cycling losses. The laboratory tests showed that when the tested machines cycled from max speed to off: "there is very little energy penalty." On the other hand when the cycling occurs under low load conditions: "there is still a noticeable energy penalty…" and "When cycling on, the DHP targets an initially higher output than required and overshoots the optimal performance range" (ibid, 26).
- While the listed SEERs of the lab-tested units are 25 and 23, the laboratory-tested SEERs were 20.3 and 15.5 respectively. The authors note that they had a difficult time duplicating the intermediate speed operating points and difficulty controlling the units to the desired speed (ibid, 29). The authors conclude: "Unfortunately, it does not appear that either manufacturer's SEER rating is well represented by our testing" (ibid, 30).
- While the listed EERs are 14.46 and 12.9, the lab test EERs were 11.4 and 10.9 respectively (ibid, 29).

Cheung & Braun (2010) mapped the performance of a variable speed ductless heat pump in the heating mode. The paper presents the results as an empirical model of the unit that was tested in the laboratory. Figure 2 presents the results of the mapping in the heating mode at high indoor airflow, a variety of outdoor temperatures, and compressor speeds from full capacity to 25% capacity. This figure shows the generalized performance of these machines. At higher compressor speeds the efficiency of the machine is diminished (lower COP and lower EER).

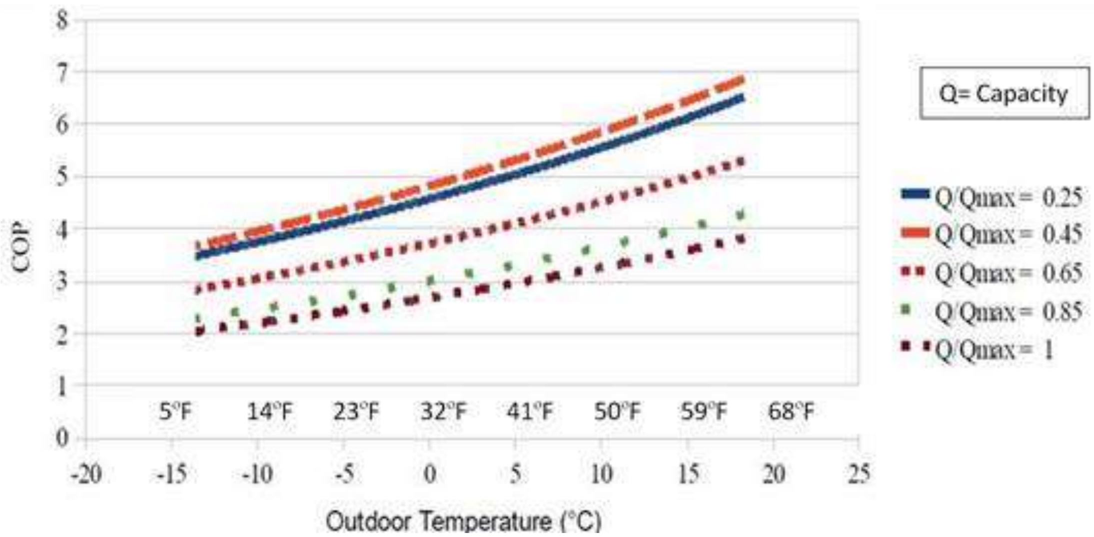

Figure 2. Performance Map of a Single Head Ductless Heat Pump in Heating

Munk et al. 2014 reported on two variable speed heat pumps installed in an unoccupied home identified as Campbell Creek #1 (CC1). That home is a "standard builder model" of construction typical for the region. For the research reported in this paper, the house was retrofitted with two ducted variable speed heat pumps. These heat pumps performed at 13% and 9% less than their rated SEERs (19.1 and 19.2). The same machines performed at 4% and 26% below their rated Heating Seasonal Performance Factors (HSPF) of 10.5.

Domitrovic 2015 reports on the same house, CC1. The retrofit variable speed heat pumps were upsized by 0.5 tons each, to 2 tons upstairs and 3 tons downstairs. In the baseline configuration, the home had two 13 SEER, 7.7 HSPF single speed heat pumps (1.5 tons downstairs, 2.5 tons upstairs).

The Domitrovic presentation estimates a heating savings of 22% for one year and 42% savings for the next year with most of that savings occurring in the colder temperatures and on the downstairs unit. The estimated savings are the result of at least two factors: upsizing the units to virtually eliminate electric resistance back up use (a major portion of the energy consumption in the base case, particularly on the downstairs unit) and the potentially improved efficiency of the heat pumps. Graphs of the downstairs unit in both Domitrovic and Munk show the baseline downstairs unit with far too little capacity to meet the load.

CVRH Methodology

In the primary research covered in this paper, each test home was retrofitted with a monitoring and control system as well as with reference "yardstick" heating and cooling systems. The reference cooling systems are conventional split system air conditioners operating at a single speed. The reference heating systems are electric resistance heaters in each room. The reference systems, including their ducts, are located completely indoors (except for the AC condensing unit) so no duct conduction or leakage effects occur. Figure 3 shows the reference AC and heating systems in one of the houses.

The reference systems and the VS systems are controlled by the monitoring and control system. The systems in each house run the same thermostat schedules with the same internal heat gains. The VS system in each house operates for two full days, then the conventional (reference yardstick) system operates for two full days. This rotation is followed throughout the summer and winter test periods.

Figure 3. Reference "Yardstick" AC and Heating Systems

The monitoring and control system recorded over 100 data points every 20 seconds and compiled the averages or sums (as appropriate every minute). Data points included temperatures, pressures, humidity, heat flux, energy use, on/off status, wind speed and horizontal solar radiation. The system controlled the heating and cooling system, whole house fan, IAQ ventilation system, as well as latent and sensible internal gains.

The resulting data from the heating and cooling systems were compiled up to the daily level. Linear regressions of the daily heating or cooling use against daily outdoor temperature were completed. An example of the data and regression results are shown in Figure 4.

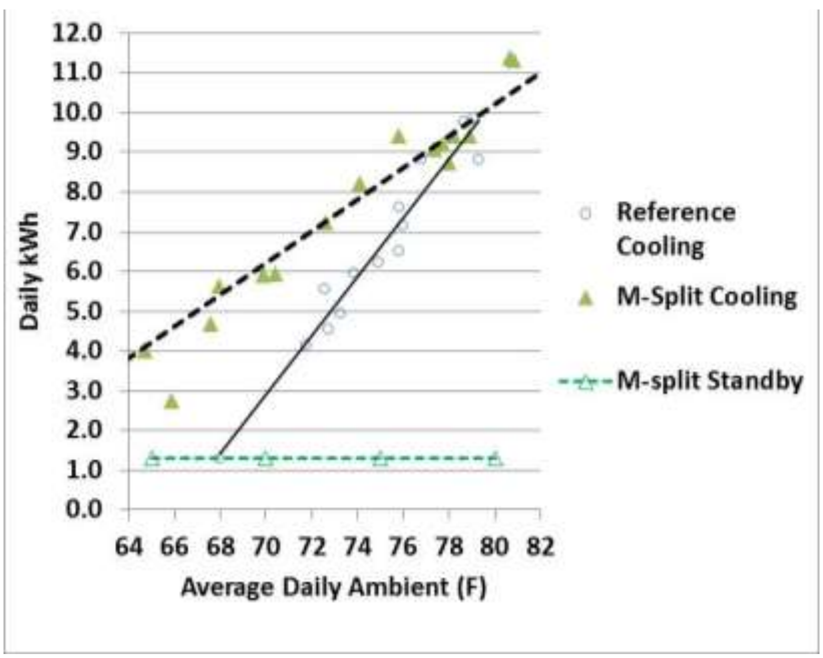

Figure 4. Reference and Multi-split Cooling Data and Regression Lines

The annual heating and cooling energy use results are standardized to a year defined by the 2013 California Energy Commission Title 24 weather file for Stockton/Sacramento.

Comparison Methodology

This study compares the energy use of the M-splits to the reference units. It looks at the anticipated differences between the M-splits and the reference units based on the standard ratings of these machines. The standard ratings used are the Seasonal Energy Efficiency Ratio (SEER) for cooling and Coefficient of

Performance (COP) for heating. Neither of these metrics is necessarily perfect. The tests that produce SEER for example are disconnected from the conditions in the field. Some disconnects are: unrealistic internal conditions for the cycling test, unrealistic assumptions about resistance to evaporator airflow and evaporator fan watt draw, etc. (ASAP 2014; Kavanaugh 2002)

Of even greater importance is that the SEER for a variable speed machine and the SEER for a single speed machine are arrived at through different tests and calculation methods. The result is that the two SEERs may not be comparable. The results of this study, including the literature search, indicate the likelihood that the SEER(VS) is not comparable to the SEER(single speed).

CVRH Houses and HVAC Components

These houses are referred to by their streets. The Caleb street experimental home (vintage 2005) was retrofitted with a four head ducted multi-split system with the ducts within the conditioned space. This system was installed as part of the manufacturer's experimental development. The system is a VS system normally used in commercial buildings. This system has a rated SEER of 14.0 and a rated EER of 9.9. The reference cooling unit is a two speed unit with a 14.8 SEER rating and an EER of 11.3. The reference cooling unit is locked in its high speed mode to produce its lowest efficiency and was operated at 350 CFM per nominal ton – slightly above the California Code minimum airflow.

The Grange street experimental home (vintage 1948) was retrofitted with a three head non-ducted multi-split system. This system is rated SEER 21.7 and EER 13.4 EER. The reference cooling unit was a two speed unit locked in high speed. The make, model and ratings are identical to the Caleb street reference unit. In the summer of 2014 the multi-split unit was operated with the inside fans set to high speed to provide the maximum sensible efficiency as desired in the hot dry California climate. The results of the experiment were evaluated two ways – with the fan kWh included, and without. In the winter of 2014-2015 the inside fans were set to "Auto".

The Mayfair street experimental home (vintage 1953) was retrofitted with a single head ducted mini-split system. This system was installed in a vented crawlspace. This system has a rated SEER of 21.5 and a 14.5 EER rating. The reference (comparison) cooling unit was a conventional split AC with a rated SEER of 16 and an EER of 13. In the summer of 2014 the Mini-split unit was operated with the inside fan set to high speed. In the winter of 2014-2015 the inside fan was set to "Auto".

Cooling Results

Energy Savings

Systems with higher SEERs are generally believed to produce cooling energy savings defined by:

$$\%Savings = \frac{(SEER_{high} - SEER_{low})}{SEER_{high}}$$

Using this formula the reference unit at Caleb would be expected to produce a 6% energy savings compared to the Multi-split. Actually the M-Split unit used 49% more energy than the reference unit, including a continuous fan that pulls 0.41 kWh per day and an outside unit that pulls 0.89 kWh per day.

Using the same formula, the Multi-split unit at Grange would be expected to save 32% compared to the reference unit. The actual results were the opposite. The M-Split used more than twice energy of the reference unit. As with the M-split unit at Caleb, the M-Split unit had high standby losses of 0.74 kWh per day. The standby losses were not characterized with respect to indoor fan energy vs. outside unit standby energy.

Using the same formula, the Mini-split unit at Mayfair would be expected to save 26% compared to the reference unit. The actual results were the opposite. The M-Split used 65% more energy than the reference unit. As with the other two M-Split units, the Mini-split unit had high standby losses of 1.1 kWh per day.

The cooling energy use of these houses is shown in two ways in the two figures below. Figure 5 shows the anticipated savings of the M-Split system and the actual additional energy use of the M-Split system as a percentage of the reference system use. Since these houses are extremely energy efficient, the percentages can be quite large for small differences in kWh. Therefore, the results are also shown as annual kWh in Figure 6.

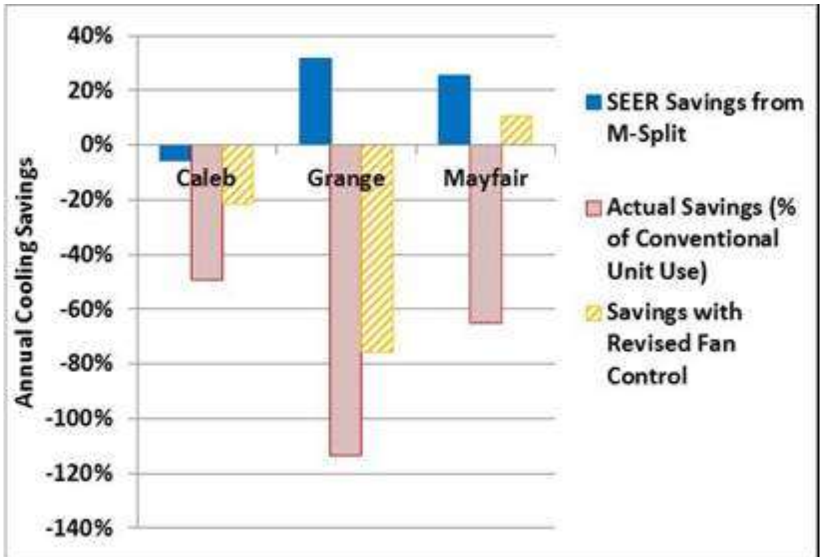

Figure 5. Monitored vs. Anticipated Cooling Savings in Percentages

The units at both Caleb and Grange underperform compared to the reference systems at the two houses. The underperformances exist even with the constant indoor fan watt draws removed.

The unit at Mayfair also underperforms with a constant high speed fan, but shows some positive potential if the indoor fan were only running when the compressor runs.

All three of these houses are low load houses so differences are magnified when viewed as percentages. As an additional perspective the annual cooling kWh from the reference units are compared to the anticipated and actual uses of the M-Split units in Figure 6.

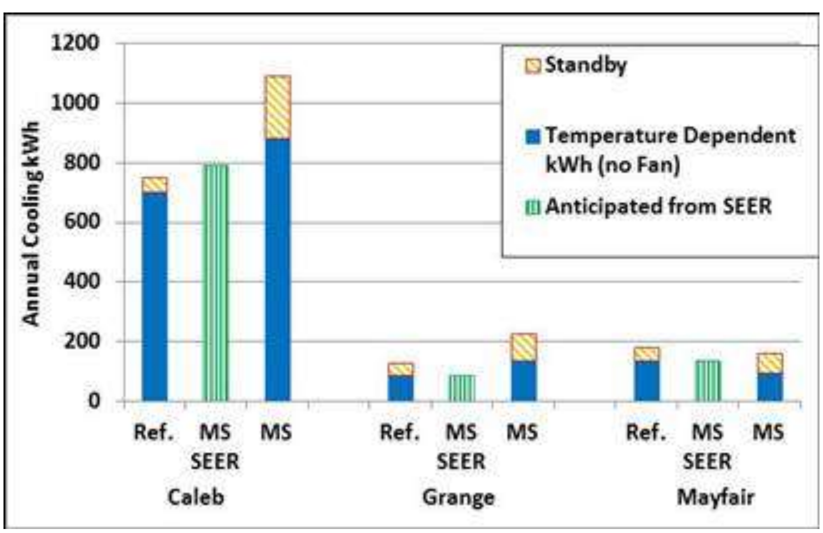

Figure 6. Monitored vs. Anticipated Cooling Savings in Annual kWh

Figure 6 again shows that the unit at Mayfair has the potential for good performance, while the other two locations' units show disappointing results.
Table 1 summarizes the annual energy consumption of the six units.

Table 1. Annual Cooling Energy Consumption

House	**Caleb**		**Grange**		**Mayfair**	
	Retrofit	Reference	Retrofit	Reference	Retrofit	Reference
AC System	Multi-split SEER14	Single Spd. SEER 14.8	Multi-split SEER 21.7	Single Spd. SEER 14.8	Mini-split SEER 21.5	Single Spd. SEER 16
Ducts	Inside	Inside	No Ducts	Inside	in Crawl	Inside
Gross Ann. Cooling	882 kWh	700 kWh	133 kWh	84 kWh	93 kWh	135 kWh
Seasonal Standby	237 kWh	49 kWh	136 kWh	43 kWh	201 kWh	43 kWh
Net Annual Cooling	1119 kWh	749 kWh	269 kWh	127 kWh	294 kWh	178 kWh

Caleb daily data and regressions. Figure 4 in the Methodology section plots the measured energy consumption of each unit against the measured 24 hour average outdoor temperature.

The R squared for the reference unit regression is 0.96. The R squared for the Multi-split is 0.94.

Grange Daily Data and Regressions

Figure 7 plots the measured energy consumption of each unit against the measured 24 hour average outdoor temperature.

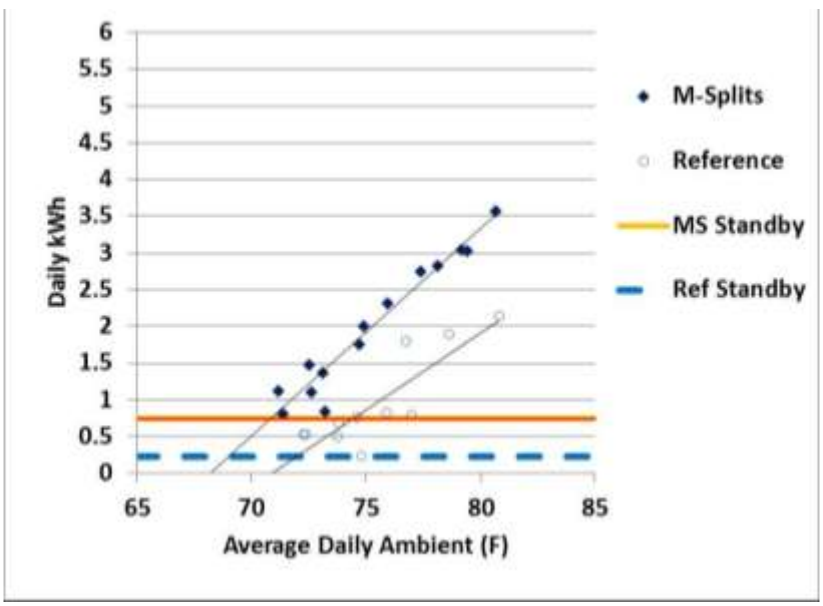

Figure 7. Grange Units – Measured Cooling Energy Consumption

The R squared for the reference unit regression is 0.83. The R squared for the Multi-split is 0.92.

Mayfair Daily Data and Regressions

Figure 8 plots the measured energy consumption of each unit against the measured 24 hour average outdoor temperature.

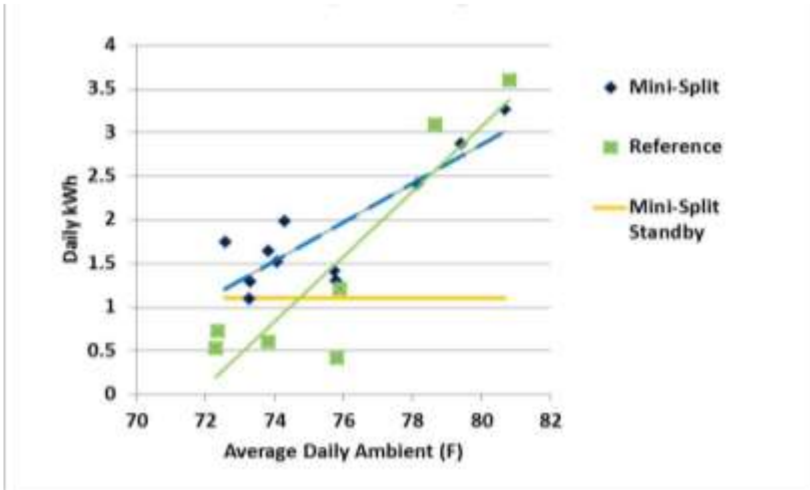

Figure 8. Mayfair Units – Measured Cooling Energy Consumption

The R squared for the reference unit regression is 0.92. The R squared for the Multi-split is 0.92.

M-Split Run Signatures

The main advantage of variable speed machines is that their speed can be reduced without significant loss of compressor efficiency. At a lower speed the size of the heat exchanger coils is larger relative to the refrigerant flow, increasing the overall system efficiency. The controls of the VS machines attempt to reduce the speed of the compressor so that the unit will run almost constantly at the lowest speed to meet the load. The tested machines fell short of this ideal during much of the cooling season. All the VS systems ran with their manufacturers' default deadbands.

Figure 9 shows a run signature of Grange, the worst performing machine. This figure shows a "shark fin" pattern on restarts after 3PM as well as attempted continuous running at low speed after the 320 minute mark. The shark fins are overly aggressive starts wherein the machine runs at higher speed than necessary.

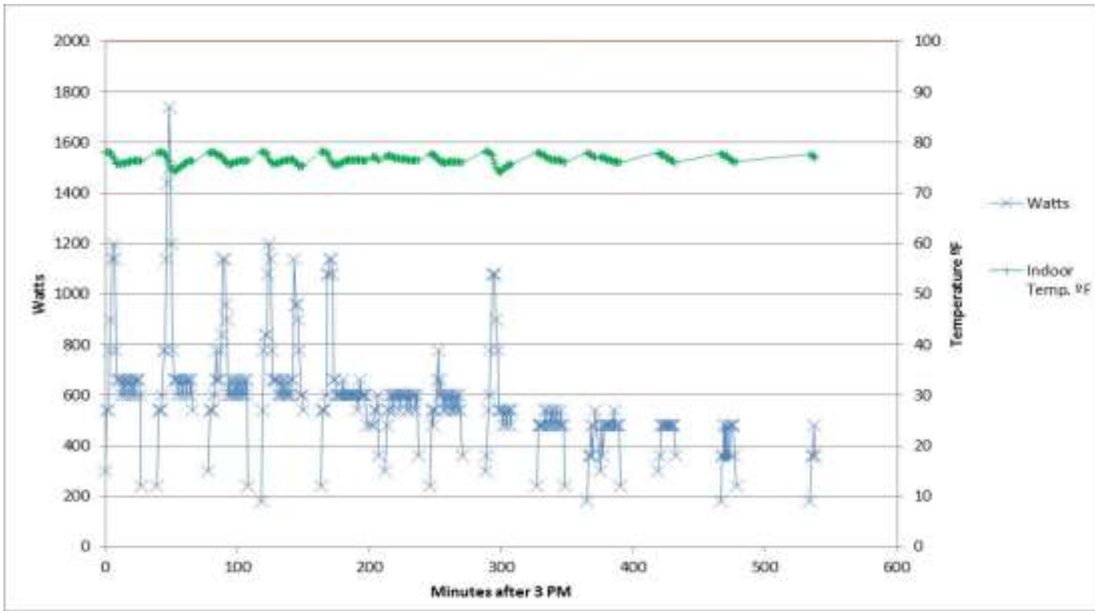

Figure 9. Grange VS Unit Run Time Signature

Figure 10 shows a run time signature at Mayfair, the best performing unit. This figure shows continuous running at low speed shortly after the spike at minute 21 to minute 300. It also shows a "shark fin" pattern on the restarts after minute 300 as the outdoor temperature and load drop.

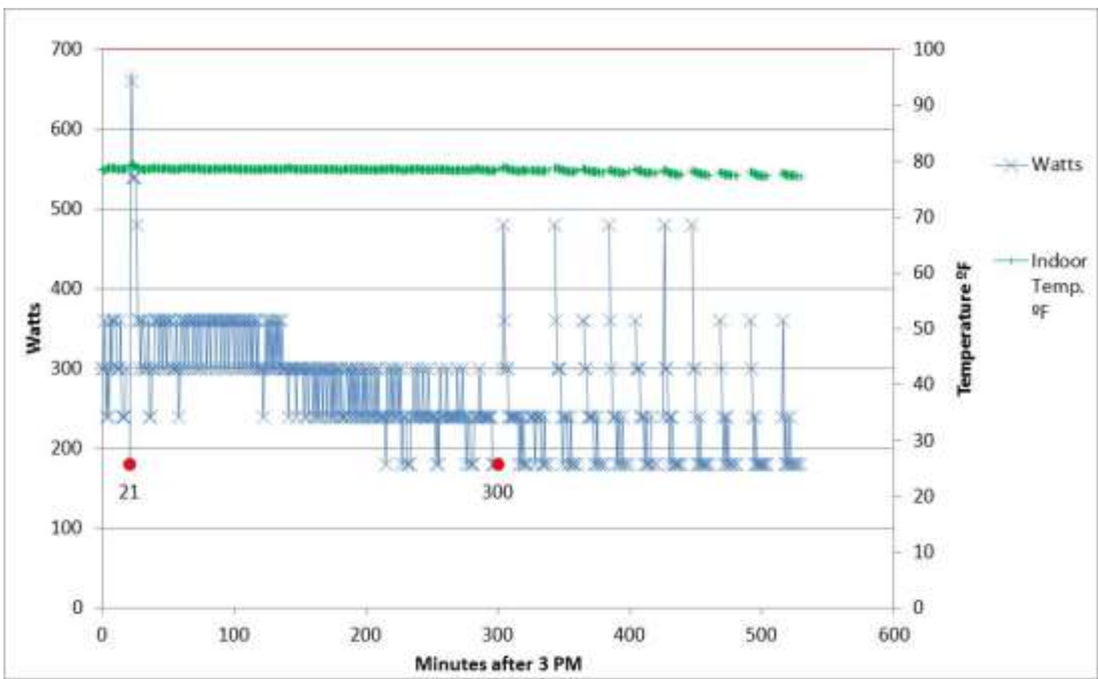

Figure 10. Mayfair VS Unit Run Time Signature

Peak Demand

On one hand, variable speed machines could reduce the peak energy consumption of air conditioners that are the cause of peak, the cause of otherwise unnecessary generation capacity and the cause of otherwise unnecessary transmission and distribution costs. Their ability to slow their speed is seen as a way of reducing peak energy demand.

On the other hand, their reported EER rating is not at their highest speed. As a result they can increase peak load above that of a single speed unit with the same rating when the thermostat settings are reduced around system peak times. Less than 50% of the residential occupancies use a constant temperature set point (BSG 1990; Parker et al. 1996; Proctor 1991; Reed 1991). And this number may be growing with the new wave of "automatic" thermostats.

Figure 11 shows the peak demand of the Grange VS unit compared to the reference unit. Both of these units are operated in the constant thermostat setting mode.

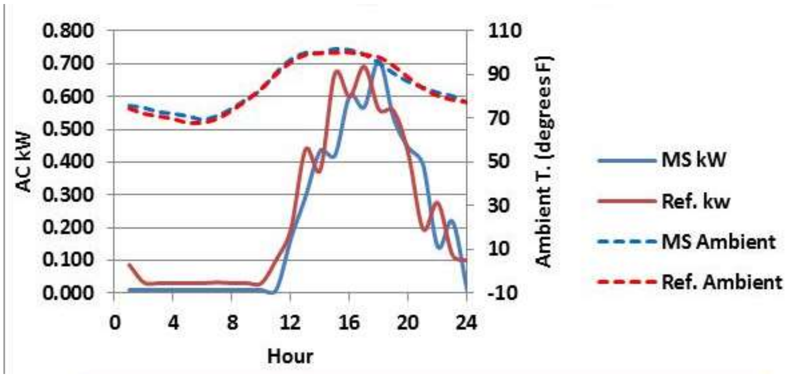

Figure 11. Grange Matched Day Peak Electrical Demand

Figure 12 shows the peak demand of the Mayfair VS unit compared to the reference unit with both units using a constant thermostat setting. There is a 34% reduction in peak demand with the VS unit. This advantage would be narrowed if the VS unit were downsized so that it was running closer to its maximum capacity.

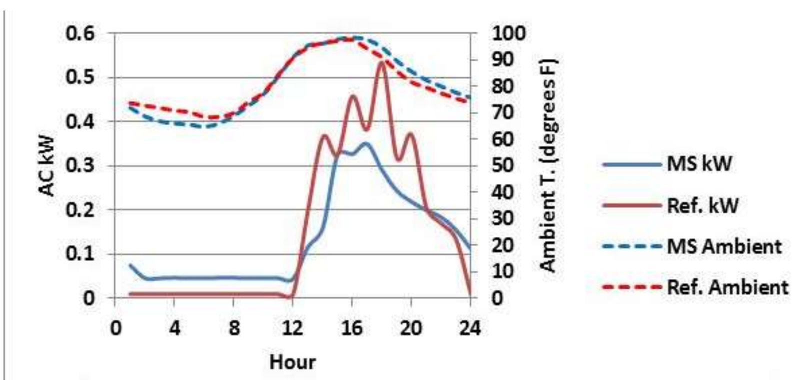

Figure 12. Mayfair Matched Day Peak Electrical Demand

Heating Results

Systems with higher COPs are generally believed to produce heating energy savings defined by:

$$\%Savings = \frac{(COP_{higheff} - COP_{loweff})}{COP_{higheff}}$$

Using this formula the M-Split unit at Caleb (COP 2.9 at 47ºF) would be expected to produce a 66% energy savings compared to the Reference resistance heaters. The actual savings was 44% for a seasonal COP of 1.77.

Using the same formula, the Multi-split unit at Grange (COP 3.51 at 47ºF) would be expected to save 72% compared to the Reference resistance heaters. The actual savings was 56% (a seasonal COP of 2.29.

Using the same formula, the Mini-split unit at Mayfair (COP 4.14 at 47ºF) would be expected to save 76% compared to the reference unit. The unit's performance approached that expectation and saved 70% compared to the Reference resistance heaters. This corresponds to a COP of 3.31.

Figure 13 shows the anticipated heating savings of the M-Split system and the actual savings as a percentage of the reference resistance system use. For Grange and Mayfair, the units were run in their "Fan Auto" modes in the winter testing.

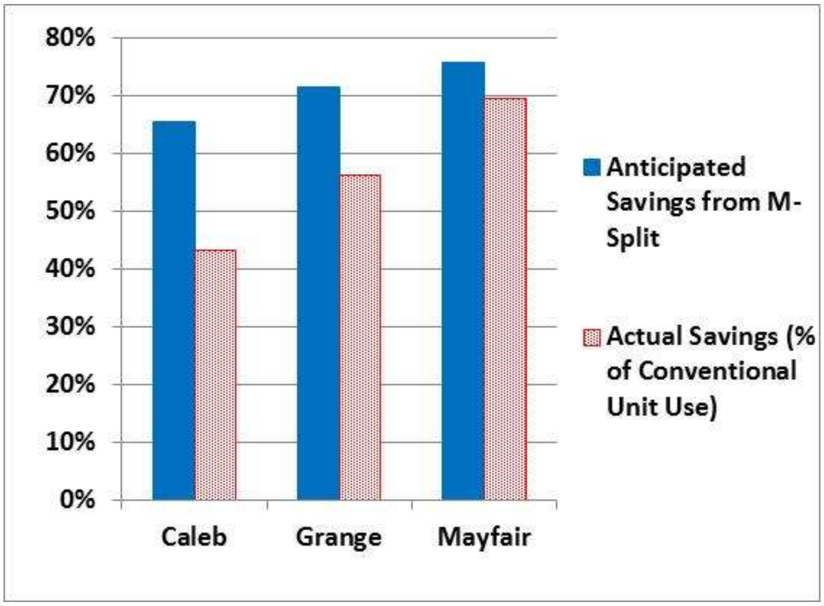

Figure 13. Variable Speed Heat Pumps Monitored vs. Anticipated Savings in Heating

Conclusions

Based on the literature review and intensive monitoring over two seasons, this study supports the following conclusions concerning variable speed heat pumps (VSHP):

1. VSHPs have potential to provide improved energy efficiency "at the box" due to the relatively low compressor "sizes" with respect to the heat exchanger "sizes".
2. Ductless VSHPs (Ductless Mini-Splits and Ductless Multi-Splits) have a distinct advantage over conventional ducted systems due to the elimination of duct losses.
3. The potential improvement in efficiency was not realized in all but one of the cases in the three test homes when the units were tested as installed by the contractors.
4. The controls and control interfaces on these machines are complex and lead to significant increases in cooling energy use. "Out of the box" many of them run the fans continuously.
5. When the fan control was reconfigured on two of the units and the units were tested in the heating mode, one unit performed near the performance implied by the ratings. The other unit did not.

6. These units may not provide the same uniform temperatures across the conditioned space as ducted systems or space conditioning equipment in every room.
7. There are disconnects between the ratings for these machines and the ratings for single speed machines. The SEER and HSPF ratings of these machines appear overly enthusiastic compared to ratings of single speed machines. This makes direct comparison based on these metrics impossible. The EERs and COPs are also not comparable to single speed machines because VSHPs are rated at a speed less than their maximum speed.
8. There is currently no consistent or achievable field verification test that can assure contractors, technicians, inspectors, or regulators that these machines are operating at their rated efficiency.

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