

Variable speed heat pumps can provide effective demand response with a soft touch

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ABSTRACT

Heat pumps and air conditioners are a class of appliances that electric utilities traditionally turn to for managing residential demand during times of grid stress, including summer and winter peaks. First-generation demand response (DR) programs utilized one-way communicating switches that cycled air conditioners / heat pumps (with prior agreement of the customer) to reduce average power consumption. Second-generation programs utilized two-way communication with smart thermostats, usually by re-setting the temperature setpoint. In both cases, some level of user discomfort could result. This has been a problem historically because DR events often coincide with extreme temperature events, when the AC unit or heat pump is needed the most. Repeated DR events could lead to many customers deciding to override the DR event or opting out of their participation in the program altogether. Recent advances in power electronics are making variable speed heat pumps more cost-effective, leading to accelerating adoption, more pronounced in some markets, primarily Europe and Asia. Moreover, these heat pumps are controlled by sophisticated management systems that can report operating data to the manufacturer “back office” or potentially to the utility or to an aggregator acting on its behalf. We report on promising results from a pilot project, in which a utility company is collaborating with an independent research organization and with a technology provider, to demonstrate that the ability to control compressor speed can be leveraged to provide high levels of demand response, while at the same time maintaining good comfort levels. In addition, we show how data available from the heat pump control systems could allow the utility or aggregator to target demand response events more effectively.

Introduction

The total electricity consumption for U.S. households in 2015 was 1267 billion kWh. The two largest single electric loads, air conditioning and space heating, were responsible for 214 billion kWh and 187 billion kWh respectively. For the South Atlantic region of the U.S., where this study takes place, the 2015 total household electricity consumption was 316 billion kWh, of which 70 billion kWh (22% of the total) were for air conditioning and 47 billion kWh (15% of the total) were for heating (U.S. Energy Information Administration, 2017). The share of peak electricity demand for cooling services in areas with similar warm and humid climate is well over 50% (Waite, et al., 2017). For heating, the picture is less clear because electricity is not the primary fuel in most locations. However, electrification of residential heating services resulting from decarbonization efforts, and increased climate variability leading to increasingly frequent extreme cold events in lower latitudes (Cohen, et al., 2019) mean that the severity of peak winter loads may increase in the next few decades. Because cooling and heating are the largest single loads for the residential sector, these have long been the target of Demand Response (DR)

programs designed to reduce generation, transmission and distribution capacity requirements in a service area by curtailing demand during a small fraction of time when grid stress is highest (Mathieu, Dyson, Callaway, & Rosenfeld, 2012). First-generation DR efforts reduced demand effectively by cycling off air conditioner (AC) units via switches controlled by pagers, FM data radio and other one-way broadcast technologies, but left homeowners with little control on their comfort (Sullivan, Bode, Kellow, Woehleke, & Eto, 2013). Second-generation DR programs took advantage of the introduction of web-enabled smart thermostats and allowed customers to opt-out if they so desired, for example if comfort levels were compromised excessively. Some smart thermostat DR programs reduced overall load indirectly by altering thermostat setpoints, while still allowing for user opt-out (Siano, 2014). Both first- and second-generation DR programs were modeled on the assumption that AC and heat pump compressors are either on or off. Recent advances in power electronics are making it possible to run the compressor, and the associated blower fans, at speeds anywhere between 25% to over 100% of nominal full speed. This has significant advantages from several points of view. For instance, continuously adjustable capacity means that the control system can maintain temperatures very close to the setpoint, rather than continually oscillating within a deadband. Comfort is also enhanced as a consequence of fewer periods of transient operation, resulting in better temperature and humidity control (Rice & Fischer, 1985).

With variable capacity heat pumps, there are better options available for participating in DR. Reducing the capacity of the system, rather than cycling on and off either by direct control or temperature setpoint reset, retains partial flow of conditioned air and good humidity control. Furthermore, by operating the system at reduced capacity, the system coefficient of performance (COP) improves considerably, so that the percent reduction in comfort is smaller than the percent reduction in electricity consumption. As a result, we hypothesize that the magnitude of the perceived reduction in individual customer comfort is smaller than the corresponding reduction of electric load associated with heat pump or AC operation in the service area affected. To test this hypothesis, we formed a team consisting of researchers from a utility company operating in the Southeastern U.S. (Duke Energy), from an independent research organization (Electric Power Research Institute), and from a heat pump manufacturer (Trane), to implement a pilot program involving Duke Energy customers who own a variable capacity heat pump produced by Trane. The pilot project was set up with the long-term view of implementing a scaled-up utility program that could include various incentives, such as rebates on the purchase of advanced heat pump equipment, compensation for participation in a DR program, or other incentives. In the pilot program, a relatively small number of customers agreed to having monitoring equipment installed at their premises, and to accepting demand response events initiated during certain weather events, such as high ambient temperatures during the cooling season or low ambient temperatures during the heating season. The goal of this study was to estimate the load reduction resulting from a DR event and its associated effect on customer comfort, as a function of weather conditions.

Methodology

The demand response capabilities of the variable speed heat pumps are tested at twenty different demonstration sites in Florida (individually referred to as Sites 1-20), all of which are residential single-family buildings. **Error! Reference source not found..** Eleven of the units were enrolled in the DR program starting in summer 2019, and the remaining units were added in late 2020. The heat pumps range from two to five tons of refrigeration capacity. Some sites have

multiple units serving separate zones within the house. All heat pump units have on-board instrumentation that relays the system status to a communicating controller, which in turn sends and receives information to and from the manufacturer's diagnostics portal. The portal dashboard shows a list of all thermostats that are registered and their current status, sourced from a database that continuously records data from the unit controllers. For each connected thermostat, the portal can show current readings from the onboard instrumentation. This includes the measured outdoor and indoor temperature and relative humidity, cooling and heating setpoint, static pressure, indoor blower air flow rate, and compressor speed. The information is stored in the manufacturer database and can be retrieved for further analysis. Control and sensor data are sent to the portal when data point values change by a minimum threshold, to minimize bandwidth and storage requirements.

Because of the relatively small size of this demonstration, the Trane diagnostics portal was chosen over a more scalable OpenADR or similar standards-based implementation. DR signals could be sent manually from the portal to various combinations of the Wi-Fi connected units, with durations up to four hours in increments of 15 minutes. Three of the sites (4, 5, and 11) were also instrumented with independent (EPRI) monitoring units which transferred data to a central database through a cell modem, at a 1-minute interval.

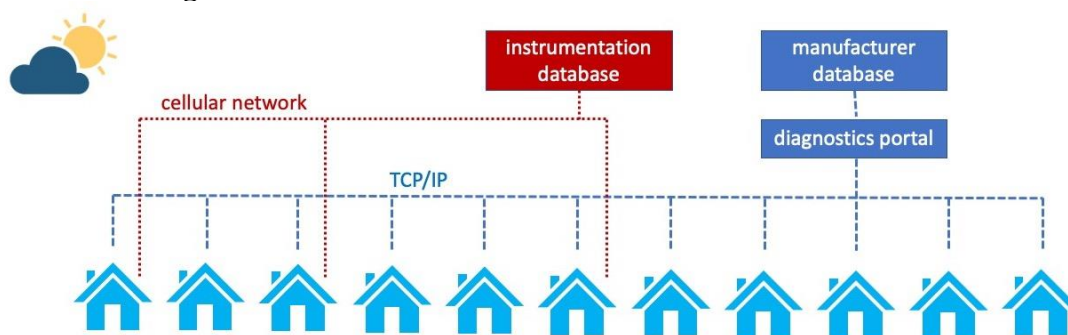


Figure 1. DR control and monitoring setup, showing manufacturer communications (via TCP/IP) and independent monitoring (via cell modem).

The DR control and monitoring setup is shown schematically in **Error! Reference source not found.** The role of the independent instrumentation serves the dual purpose of verifying manufacturer instrumentation data, and to augment the data with information that is not available from the manufacturer portal, including the power consumption. The strategy of the study was to send DR signals during certain weather events (e.g. particularly warm cooling days or particularly cold heating days), and to record the response of the system. The data points captured by the manufacturer instrumentation and by the EPRI instrumentation before, during and after DR events are summarized in Table 1.

Table 1. Data captured by system onboard controller, sent to the manufacturer database, and by the EPRI independent instrumentation, sent to the EPRI database.

	Manufacturer monitoring	unit	EPRI monitoring	unit
Indoor space	Temperature	°F	Temperature	°C
	RH	%	RH	%

	Manufacturer monitoring	unit	EPRI monitoring	unit
	Setpoint	°F		
Air handler	Air flow	% of max	Power	kW
	Liquid temperature	°F	Supply temperature	°C
	Gas temperature	°F	Return temperature	°C
	Superheat	°F		
Outdoor unit	Temperature	°F	Temperature	°C
	RH	%	RH	%
	Compressor Speed	%	Power	kW

Results

Understanding the DR potential of a fleet of variable capacity heat pumps

Existing DR programs rely on large numbers of end use devices to respond to a signal, in such a way that the collective response is close to the expected magnitude. The response of an individual end-use device depends on whether the device is active and on whether it can respond under its operating conditions. Statistics on these parameters are increasingly being collected by smart thermostats, however they still do not provide a complete picture. For example, the on/off state of a device does not provide information on the change in power consumption following a state switch. On the other hand, for variable capacity heat pumps like the ones considered in this project, while direct measurements of power consumption are not available, it should be possible to estimate power consumption at any given time based on known compressor speed and other sensor measurements.

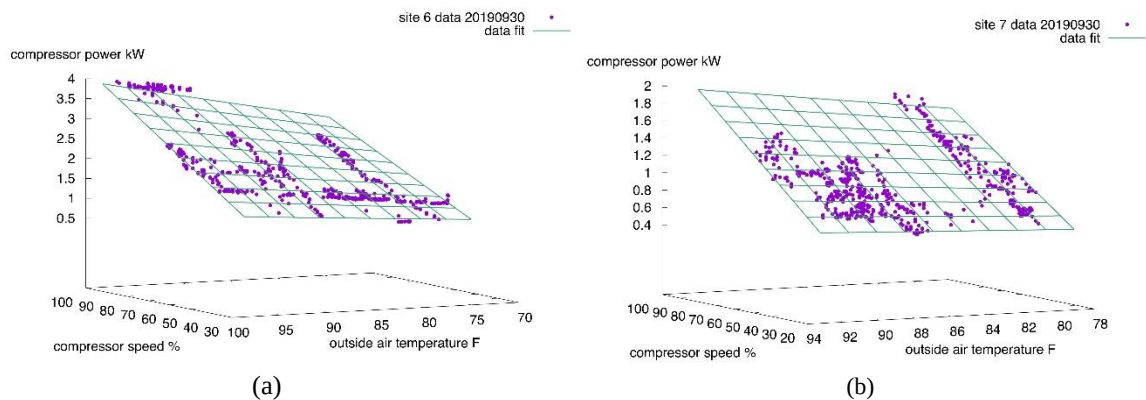


Figure 2. Relationship between compressor power, compressor speed and outside air temperature for a five-ton unit (a) and a three-ton unit (b). Note that the smaller unit operated at full speed even at low ambient temperature, to respond to a large setpoint change in the schedule.

The mechanical work done by the compressor in a variable capacity heat pump can be assumed to depend on the flow rate of the refrigerant, and on the compression ratio between the condenser and the evaporator. We consider the case of cooling mode operation. Under the assumption that evaporator conditions are approximately constant (because indoor setpoints are generally stable), it may be assumed that flow rate is directly proportional to compressor speed. The compression ratio is a nonlinear function of the outdoor temperature, which can be approximated as a power law. Thus, the electric power consumption P of the compressor can be expressed as

$$P = AS(B + T)^C \quad \text{Equation 1}$$

where A , B and C are constants, S is the compressor speed and T is temperature. Data from two sites, 6 and 7, where EPRI monitoring was installed, were collected. A five-ton cooling capacity unit is installed at site 6, while a three-ton unit is installed at site 7, as shown in Figure 2. A least-squares fit of **Error! Reference source not found.** to the data produces $A = 0.000118425$, $B = 0.000999942$ and $C = 1.26082$ for the five-ton unit and $A = 0.0000681833$, $B = 0.000999956$ and $C = 1.25951$. The ratio of the constants A for the three-ton and the five-ton units is 0.575, close to the expected 0.6 ratio of the machine nominal ratings. The constants B and C are virtually the same, giving us good confidence that the heuristic model of **Error! Reference source not found.** describes the same thermophysical mechanisms in the refrigeration cycle, and that an accurate measure of power can be obtained given values of compressor speed and temperature. The practical consequence of the results reported here is that it is possible to estimate the power consumption of a variable capacity heat pump very accurately based on the machine rating, the outside air temperature, and the compressor speed, all of which are known by the manufacturer and available in real time, and historically on their database, for thousands of installed units at high temporal resolution, and potentially spatial resolution.

It is important to understand the collective effect of a DR event, with the understanding that the sample is limited and that we cannot determine statistically significant DR capacity indicators based on this. We therefore only report a summary of the results of the experiments performed during this work, with the expectation of larger studies in the near future. Using the manufacturer diagnostics portal, a test requesting all test sites (11 total at the time) to participate in a DR event was conducted on June 26th, 2020. The compressor power of the connected variable capacity heat pumps starting 30 minutes before a 30-minute DR event and ending 30 minutes after the DR event is shown in Figure 3(a). We observe that, collectively, this DR event produces good demand reduction from the units. All the units resumed normal operation after the event, with most ramping up capacity to provide additional cooling to the space to return to setpoint.

The indoor temperature and thermostat setpoint are two parameters that are essential in understanding the variable capacity heat pump response to DR events. Figure 3(b) shows the deviation between indoor temperature and thermostat setpoint, calculated by subtracting the setpoint from indoor temperature, so a deviation of -1°F means the indoor temperature is 1°F below the thermostat setpoint. The thermostat setpoint was unaltered for the periods before, during, and after the event except for site 5 and 11b. The setpoint for site 5 changes from 80°F to 74°F then to 77°F during the event, where it remains for the remainder of the test. This manual setpoint adjustment may be a result of perceived loss of comfort, although the temperature had only changed by $^\circ\text{F}$ when the first setpoint change occurred. For site 11b, the setpoint adjustment

was likely due to a scheduled change. At site 4b, a large deviation from setpoint existed even before the event – possibly a consequence of open windows or perhaps an undersized unit. Most of the units did not show a significant increase in deviation from setpoint during the DR event, demonstrating the variable capacity heat pumps’ ability to maintain good comfort levels even when operating at a reduced capacity, partially due to the increased COP.

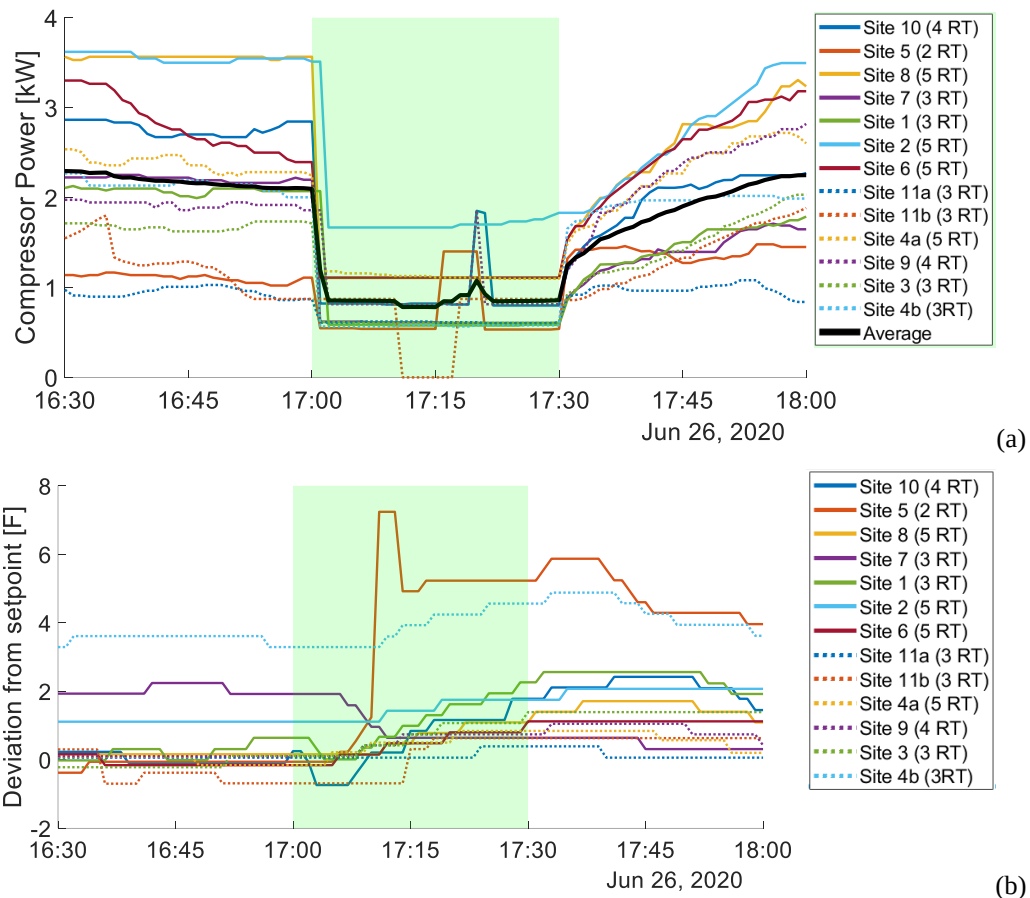


Figure 3. Collective DR response of all test units on June 26, 2019, showing compressor power – with average shown as a thick black line (a) and space temperature deviation from setpoint (b). Each heat pump is denoted by an ID number, while the DR period is shaded in green.

A 1-hour DR event on November 5, 2020, is shown in Figure 4, with data from all except 3 enrolled units. The DR event started at 2:45PM and the results are presented in the same fashion as the previous example. Figure 4(a) shows that only 1 unit (site 16) was operating at its maximum compressor speed prior to the event, and several units are operating above 50% capacity. All of those units saw a reduction in compressor speed at the start of the event, and several units saw spikes in compressor speed during the course of the event. The manufacturer indicated that the spikes are likely due to a control algorithm that requires short bursts of high compressor speed for oil return cycles during low-speed operation. A closer inspection at the deviation from setpoint in Figure 4(b) shows the spikes in compressor speed during the DR event is unlikely to be caused by customer discomfort, since all but 1 site (site 16) were at or below setpoint during the entirety of the DR event as well as 1 hour before and after the event. The unit at site 16 was operating at 100% capacity before the event and ramped up towards 100% shortly after the event ended and was the only unit to show significant response. The space temperature

deviation from setpoint at this site during the DR event increased from 2.5F to 4.9F and decreased to 3.8F 1 hour after the event. It should be noted that the setpoint for this site was a low 70F, while setpoints at the other sites range between 74F and 81F, which may also contribute to the higher deviation. Open windows or doors could also cause the inability of the system to maintain temperature. The negative deviation from setpoint at sites 14 and 15 corresponds to the corresponding heat pumps not active (presumably because they are in cooling mode). The overall results actually show much lower deviations from setpoint for most of the units when compared to the 30min event in June, likely due to a combination of two factors: first, most units were running at low compressor speed already before the event, so speed could not be reduced significantly by the DR signal. Second, the low latent load made it easier for the units to maintain comfort conditions at low compressor speed.

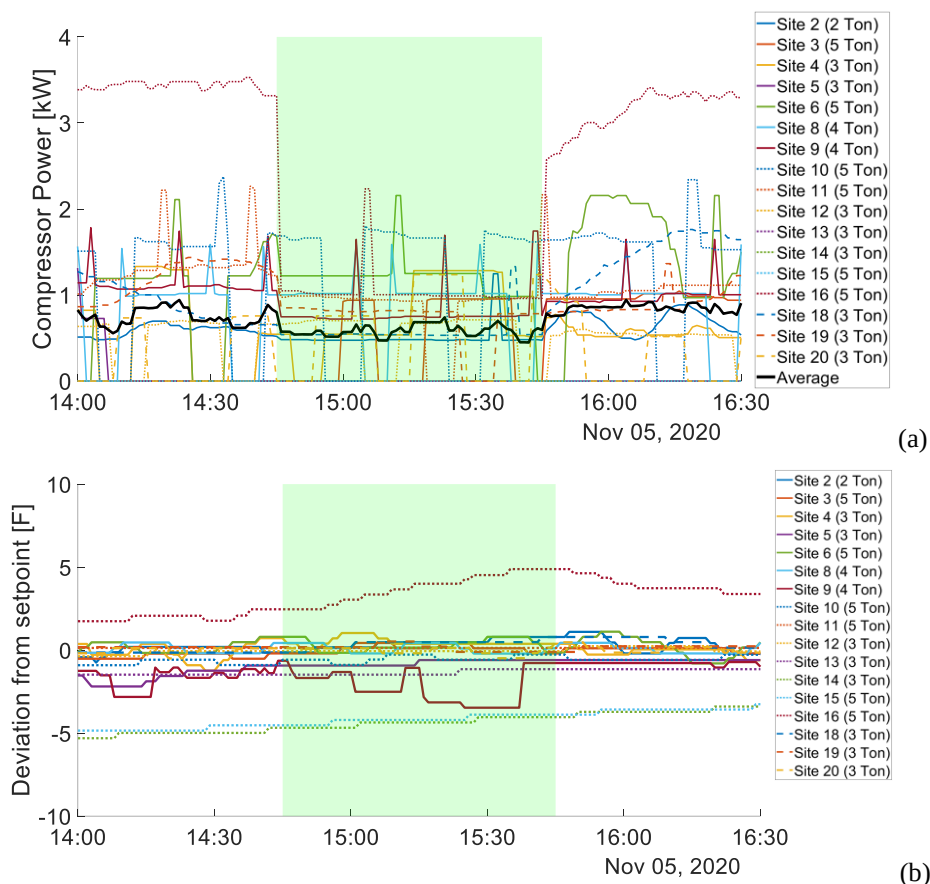


Figure 4. Collective DR response of all test units on November 5, 2020, showing compressor power – with average shown as a thick black line (a), and space temperature deviation from setpoint (b). Each heat pump is denoted by an ID number, while the DR period is shaded in green.

Figure 5 shows the compressor speed and deviation from setpoint for all connected units on a typical day without DR events in November. Due to the mild temperatures experienced on this day, the average compressor speed is quite low throughout the day, with a small spike after midnight and another starting around 6PM. We see several units occasionally and briefly cycle to 64% and 67% (similar to the hour-long DR event), likely due to oil return cycles at default settings by the manufacturer. It is also interesting to see the deviation from setpoint of the units, where large spikes can be observed around noon for 3 units, and a large spike in the evening for

1 unit. This provides information on the occupant habits at the host sites, where some of the units are set to a much higher setpoint during the day (likely coincident with lower building occupancy) and reduced at night. The majority of the units, all in cooling mode, maintained a deviation less than 3°F consistently, demonstrating again the variable capacity units' ability to provide high customer comfort.

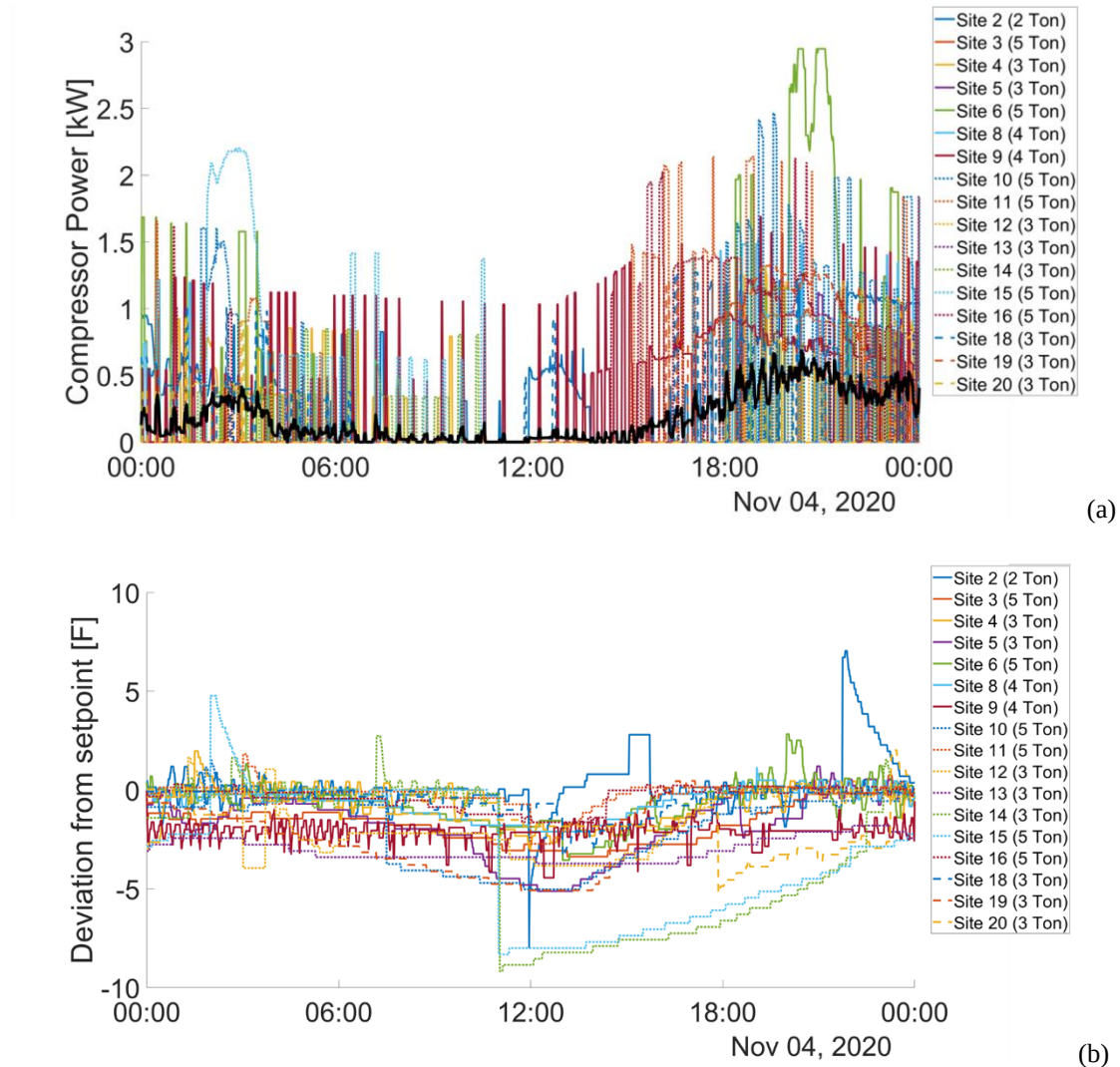
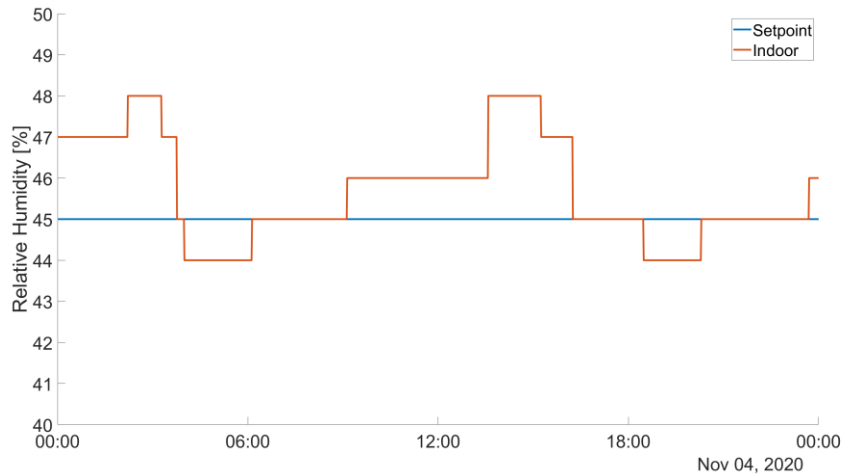
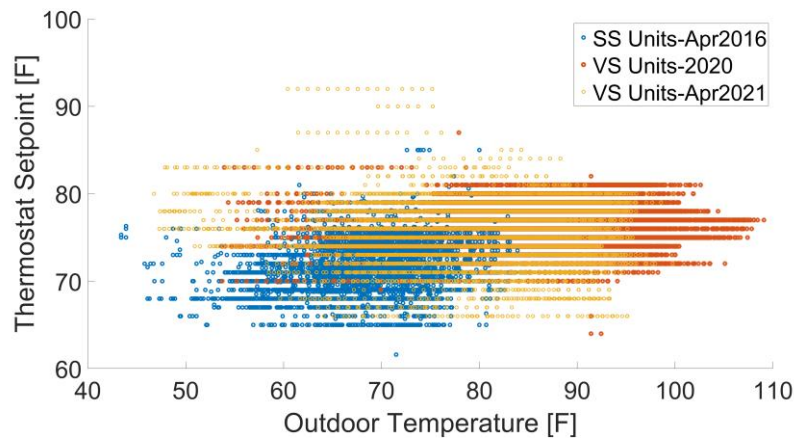


Figure 5. Collective data of all test units on a typical baseline day with no DR event, showing compressor power – with average for all compressors shown as a thick black line (a) and deviation from setpoint (b). Each heat pump is denoted by a site number and rated capacity.



Other factors influencing compressor speed may be disturbances in temperature due to indoor air flows, solar gains, humidity and cycling of the compressor at low speed. The data also reveals whether the unit is sized appropriately for the structure it is installed in. Moreover, the thermal characteristics of each house where a variable capacity heat pump is installed can be calculated by analyzing the space temperature response to a step change such as a scheduled setpoint change or a DR event. These data can therefore provide real-time status of DR availability, as well as the capacity to forecast this for time horizons commensurate with weather forecasting.



(a)

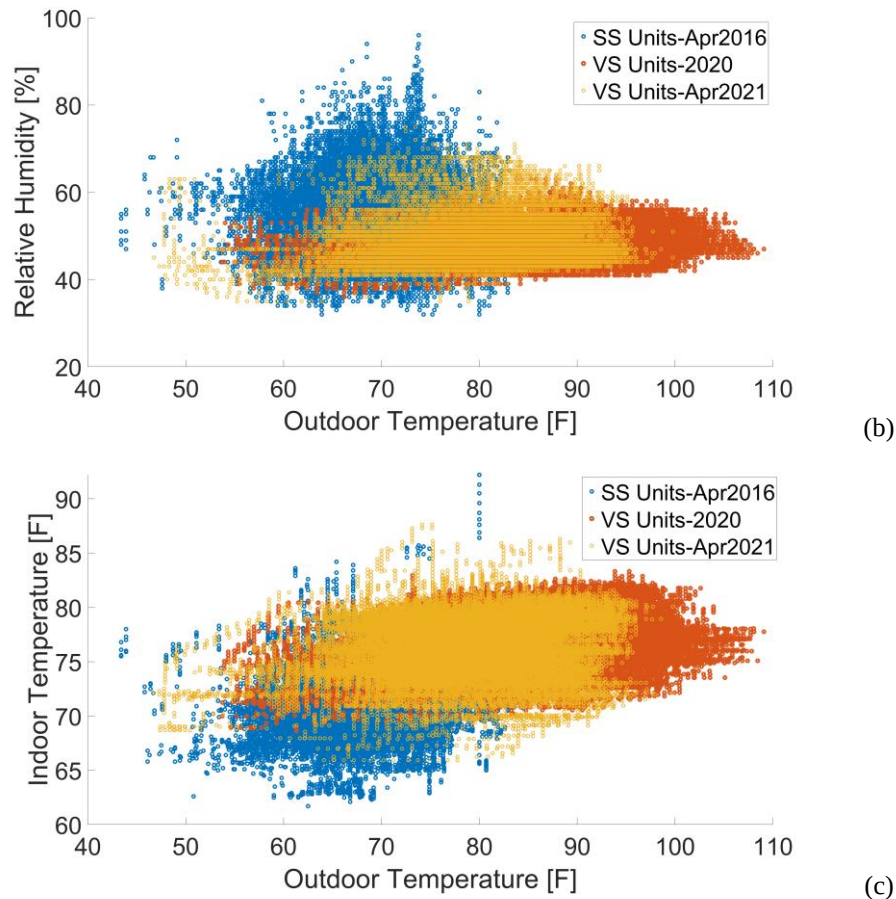


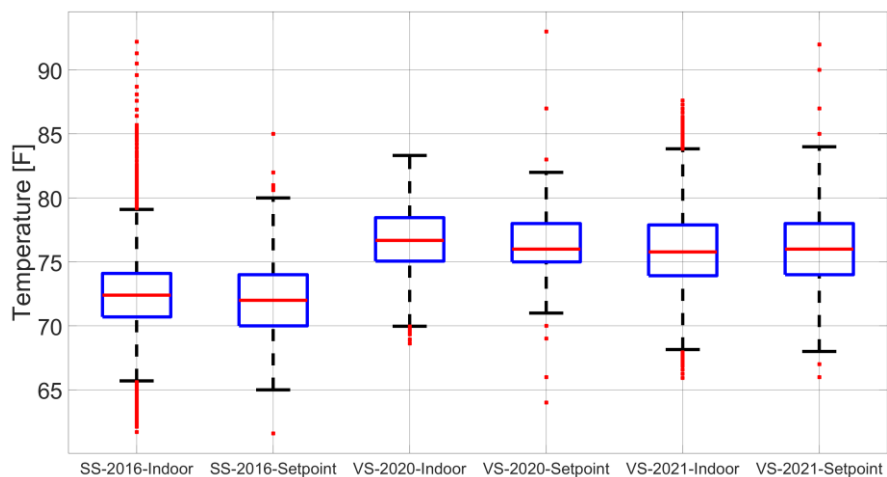
Figure 6. Collective data of all test units compared against a fleet of single speed heat pumps, showing thermostat setpoint (a), indoor relative humidity (b), and indoor temperature (c) for a range of outdoor temperatures. Variable capacity data is separated into data from 2020 over several months and April 2021.

Our results from this set of field experiments indicate that customer comfort is maintained during DR events, with very infrequent manual temperature resets. This is likely a function of the capacity of VC systems to maintain very tight control of relative humidity, along with the ability of VC systems to provide a good fraction of full capacity even during DR events. The benefits to customer comfort of variable capacity heat pumps resulting from humidity control advantages can be best illustrated by comparing houses with variable capacity heat pumps to those with single speed systems. While customer behavior such as thermostat setpoints and occupancy will vary from home to home, these effects can be normalized to an extent by including a large sample of homes. The data from variable capacity heat pumps under study here is compared to a dataset of single speed systems totaling 148 homes, with the observation period spanning the month of April 2016. Similar to the variable capacity systems, the single speed systems were installed in various locations in central Florida. Key parameters such as thermostat setpoint, indoor/outdoor temperature and indoor relative humidity were monitored. Figure 6 shows the comparison of indoor conditions between single (blue) and variable speed systems over a range of outdoor temperatures, the variable speed data are separated into two groups, one for 2020 over several months (red), and one for April 2021 (yellow) to match the typical climate for that month. It should be noted the variable capacity data did not include any DR events for a

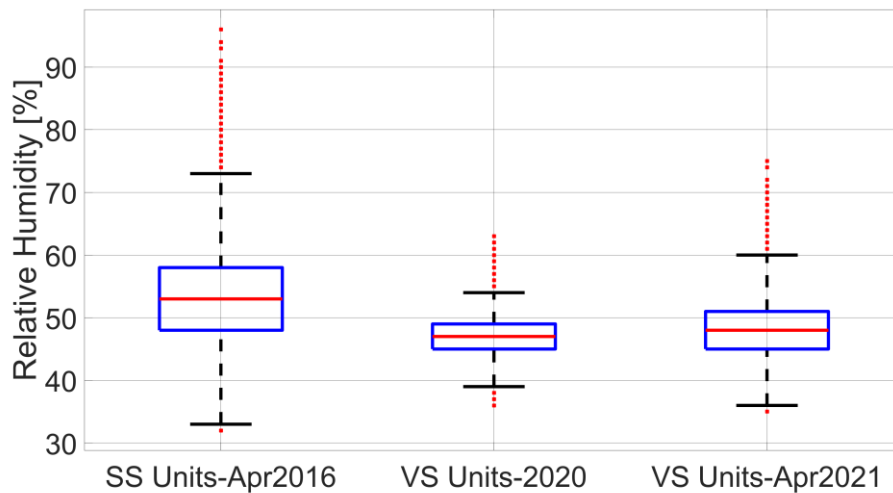
more direct and fair comparison against the single speed baseline. Since the systems were observed during different time periods, the range of outdoor temperatures were slightly different. The comparison only includes data when the system is operating and in cooling mode. Inspection of the figure reveals that compressor speed is indeed proportional to outside temperature, with data clustered around lines whose slope is determined by the combination of the thermal losses of the structure and the capacity of the unit.

Figure 6(a) shows the thermostat setpoint of the homes. The single speed systems ranged from 65F to 75F while the variable speed system ranged from 70F up to 82F. Interestingly, the setpoint for variable speed systems remained in that range even when the outdoor temperature increased over 90F. The higher setpoints for the variable capacity system are likely a consequence of their ability to precisely control indoor temperature and relative humidity, the latter of which plays a significant role in perceived comfort in humid climates experienced in Florida. This can be seen in Figure 6(b), which compares the indoor relative humidity of the homes. The variable speed units are able to maintain the relative humidity between 40%-60% while relative humidity covered a larger range, from 35%-90%, for the single speed systems. It should be noted that outdoor relative humidity was not monitored and would have an effect on the indoor conditions, but the variations should be minor since the systems are located in similar climates. Figure 7 shows the comparisons of the same data in whisker plot format, and it more clearly shows the higher thermostat setpoint and indoor temperature for the variable speed systems. Figure 7(b) in particular, highlights the wide range of relative humidity for the single speed systems, while the variable speed systems maintain much tighter control.

These comparisons against single speed systems exemplifies the benefits of variable capacity systems in terms of occupant comfort. The reduction in thermostat setpoints translates to a reduction of thermal load of the homes under similar outdoor temperature, internal and solar gains, in turn resulting in higher energy efficiency. If deployed on a large enough scale, fleets of variable capacity systems may reduce the overall grid demand caused by residential HVAC systems, particularly during extreme weather conditions. When coupled with their potential to shed load during DR events, variable capacity systems are flexible grid resources that also maintain comfortable indoor conditions for customers. The enhanced comfort for customers also reduces the likelihood of customers opting out of DR events or exiting DR programs entirely.



(a)



(b)

Figure 7. Whisker plot of thermostat setpoint (a), indoor relative humidity (b), and indoor temperature (c) for a range of outdoor temperatures. Variable capacity data is separated into data from 2020 over several months and April 2021.

Discussion

Although the number of participants in this study was limited, this study provides strong evidence that variable capacity systems offer more flexibility than corresponding single-speed units for demand response and for its closely related concept, load flexibility. Demand response has traditionally been associated with a utility's need to reduce load during times of grid stress, while load flexibility is an evolution of DR associated with the evolving need to match demand to variable renewable generation. For traditional DR, the need to reduce demand usually coincides with severe weather conditions (very hot or very cold). In this case, a well-designed system may very well be working at or near maximum capacity, but DR with variable capacity equipment merely reduces its capacity instead of cycling the system off like conventional equipment, so the impact on comfort (and perception thereof) is more limited. The well-known fact that a variable capacity system at part load is more efficient than at full load also contributes to mitigating the reduction in thermal comfort in comparison to a single speed system at the same average load reduction. The ability of fleet of heat pumps to provide a flexible load also depends on the season. In hot and humid summer conditions, there is more capacity to reduce load rather than to increase it, and this is a good match for traditional DR programs where the need is usually for a system load reduction. In shoulder seasons, on the other hand, when systems are at part load, variable capacity heat pumps offer opportunities for load flexibility, for example to compensate for intermittent PV generation on the grid. Here too, the ability to vary load continuously means better load flexibility than with conventional systems, where cycling units on and off is limited by the compressor deadtime between start and stop. It should also be noted that variable capacity units offer better control of humidity than units that cycle, because they can vary the ratio of compressor speed and fan speed to control moisture.

Because variable capacity units depend on more sophisticated controls, the information available is far more than with conventional units, even those where smart thermostats have been installed. As a consequence, it is increasingly possible to characterize the thermal response of a house to changes in capacity. This can be done in a variety of ways - passively, by observing the

temperature response as a function of setpoint changes or capacity reductions during a DR event, or actively, by perturbing the capacity by a small amount, imperceptible to the user, and observing the resulting temperature change. Knowledge of the thermal response of a house can be helpful to target DR levels to individual homes. For example, houses with slow response (good insulation, high thermal mass) may be able to support longer DR times than ones with faster response and may thus be targeted differently. The availability of information on the state of a structure and on its thermal response may also be useful in estimating the overall DR capacity / flexibility of a service region, for real-time response and for forecasting purposes.

Finally, the nature of modern variable HVAC controls is difficult to access by traditional utility DR implementations. Enrolling and controlling these sophisticated devices can now be done remotely in contactless way with no need for additional hardware installed by the utility or the customer. This makes future DR programs with variable capacity equipment potentially cheaper to setup and administer. Customers also benefit from transparency and cost effectiveness of the program, which could lead to higher utility cost savings

References

- Cohen, J., Zhang, X., Francis, J., Jung, T., Kwok, R., Overland, J., . . . Feldstein, S. (2019). Divergent consensuses on Arctic amplification influence on midlatitude severe winter weather. *Nature Climate Change*, 1-10.
- Mathieu, J., Dyson, M., Callaway, D., & Rosenfeld, A. (2012). Using residential electric loads for fast demand response: The potential resource and revenues, the costs, and policy recommendations. *ACEEE Summer Study on Energy Efficiency in Buildings* (pp. 189-203). Monterey, CA, USA: ACEEE.
- Rice, C. K., & Fischer, S. K. (1985). A Comparative Analysis of Single-and Continuously-Variable-Capacity Heat Pump Concepts. *Proc. of the DOE/ORNL Heat Pump Conference*, (pp. 57-65). Washington, D.C., USA.
- Siano, P. (2014). Demand response and smart grids—A survey. *Renewable and sustainable energy reviews*, 30, 461-478.
- Sullivan, M., Bode, J., Kellow, B., Woehleke, S., & Eto, J. (2013). Using residential AC load control in grid operations: PG&E's ancillary service pilot. *IEEE Transactions on Smart Grid*, 4(2), 1162-1170.
- U.S. Energy Information Administration. (2017). *2015 Residential Energy Consumption Survey*. Retrieved from <https://www.eia.gov/consumption/residential/index.php>
- Waite, M., Cohen, E., Torbey, H., Piccirilli, M., Tian, Y., & Modi, V. (2017). Global trends in urban electricity demands for cooling and heating. *Energy*, 127, 786-802.