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Variable Frequency Drive Energy Savings in Refrigeration Condensers

Field Test for ComEd Emerging Technologies

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Slipstream staff member Dan Cautley contributed significantly to this project. We also appreciate the assistance of Area Mechanical with field monitoring, and the cooperation of all stores that participated in the research.

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GLOSSARY

hp	Horsepower
kWh	Kilowatt-hour
OAT	Outside air temperature
TMY	Typical Meteorological Year
VFD	Variable frequency drive

EXECUTIVE SUMMARY

On behalf of ComEd, Slipstream has performed a field study evaluating the performance of variable frequency drives (VFDs) [1] retrofitted to condenser fans in supermarket refrigeration systems.

The study comprises a pre- and post-retrofit analysis of electrical energy consumption in four supermarkets in ComEd service territory in Illinois. The full study included eight months of data collection. Each store had a different configuration of refrigeration equipment, including type, number, and size of condensers. To acquire and isolate the difference in energy consumption between pre- and post-, we ultimately measured condenser electrical power, compressor power, outside air temperature (OAT) and humidity. Analysis included direct comparison of pre- and post-VFD retrofit using both linear and non-linear regression analysis to fit patterns of energy consumption at observed OATs. Models fit to observed data were extrapolated to expected annual electrical energy savings using Typical Meteorological Year (TMY) [2] data. In all cases, we normalized the savings by condenser based on its rated horsepower. Key performance indicators included energy savings, installed cost per device, and any lessons learned from retrofits including non-energy impacts for store owners.

The VFD retrofits largely behaved as we expected. Pre-retrofit energy consumption of condenser fans showed they cycled on and off, continuously changing from stopped to full speed. We observed lower power consumption post-retrofit because VFDs modulate frequency to decrease fan speed to match fan loads. Energy savings then result when VFDs allow condenser fans to run at partial instead of full speed, largely in mild outdoor air temperatures.

Savings varied across stores and condensers. Of 16 condensers monitored, we removed two condensers from analysis due to data irregularities. We modeled pre- and post-retrofit energy consumption for the remaining 14 condensers and projected annual savings (using extrapolation to TMY) of 50 percent, +/-9 percent (90% confidence). This equates to an average energy savings per fan horsepower of 1,480 kWh/hp, +/-330 (90% confidence). The average annual dollars saved per horsepower was $150 +/-$30 (90% confidence) and the total cost of installation per horsepower was $1,170 +/-$170 (90% confidence). We based modeled savings estimates on measurements from a study period that consisted of roughly eight months, from December 2017 to July 2018.

We found, on average, that VFDs retrofitted on condensers fans in supermarkets' refrigeration systems will deliver energy savings. We did have one device that demonstrated negative savings during lower temperatures. It did exhibit some savings at higher temperatures, but net savings were negative; direct cause remains unknown. Other important lessons learned from this study are:

- Though they generally a simple technology, proper installation is still critical for VFDs, making commissioning an important aspect of each retrofit.
- Trade allies and industry professional believe VFDs have the potential to decrease maintenance costs for condenser fans, though this has not been quantified.
- Store owners may find investment in VFDs to be more attractive for stores with larger number of condensers.

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[1] Commonly, several terms refer to a motor system that allows a motor to be driven at variable speeds including adjustable speed drive (ASD), variable speed drive (VSD), adjustable frequency drive (AFD), and variable frequency drive (VFD). This report uses VFD throughout.

[2] TMY data gathered from the National Solar Radiation Database represent a single year of hourly data that best represent weather conditions over a multiyear period making results generalizable to expected annual savings. For more information see: https://nsrdb.nrel.gov/.

BACKGROUND

Refrigeration is a large source of energy consumption; in the U.S. refrigeration systems account for about 20 percent of all motor energy consumption in the commercial sector. Commercial motor measures for refrigeration have some of the highest savings potential of any energy efficiency measure in the sector.[3] Condenser fan motors are a significant portion of that energy usage. Conversations with energy efficiency program personnel and trade allies suggest that most of the existing condenser fan motors in Illinois operate at a fixed speed, although the proportion is not known precisely. Condenser fan motors retrofitted with VFDs represent a potentially important opportunity for energy savings. ComEd identified retrofit of supermarket condensers with VFDs as a significant enough opportunity to warrant further research into energy and cost savings for their customers.

The application of VFDs to refrigeration condensers in supermarkets deliver energy savings by reducing the speed of fan motors by modulating electrical frequency to just meet the current need of the condenser. As a result, the power to the motor is reduced. This savings mechanism is well understood and quantified in measures like pump and HVAC motors. However, VFDs applied specifically to commercial refrigeration remains understudied. One study investigated VFDs in commercial refrigeration but focused on compressor power instead of condenser power.[4] We are unaware of other publicly available studies specific to VFDs retrofitted to condenser fan motors in *cold-climate* refrigeration. As a result, there was value in investigating VFD retrofits in commercial refrigeration condensers in ComEd service territory.

To measure the savings in this application, ComEd approved a field study by Slipstream to test the magnitude of electrical energy savings from VFDs, cost per installed device, and any other lessons learned in their application to commercial refrigeration.

METHODS

SITE IDENTIFICATION

We identified sites for this study in an opportunistic fashion. A local supermarket chain was in the process of adding a significant number of VFDs to their portfolio stores while at the same time ComEd was interested in adding this as an incented measure. We chose four stores out of that portfolio that were in ComEd territory with coincident timing of retrofit. We chose the stores to attain a balance of the two major refrigeration system types common in that region (see below). ComEd developed a written agreement with each system owner addressing responsibilities of the parties under the project. These agreements were signed prior to starting active work on the field study.

SYSTEM DESCRIPTIONS

The study initially included 20 condensers, at four supermarkets in ComEd service territory in northern Illinois. Four condensers, while retrofitted for later use of the VFDs, were not switched on during the study period to maintain a comparison to retrofitted units. We monitored 16 of the 20 condensers for

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[3] Goetzler, William, Sutherland, Timothy, and Reis, Callie. Wed. "Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment". United States. doi:10.2172/1220812. https://www.osti.gov/servlets/purl/1220812.

[4] Bharj, R. S., and Surender Kumar. "Experimental study of power reduction from cold storage by using VFD." International Journal of Research in Management, Science & Technology, ISSN: 2321-3264.

analysis but discarded two condensers due to data irregularities, leaving 14 analyzed devices. We judged the two discarded, retrofitted condensers ineligible for analysis due to unidentified onsite events that affected power consumption through the VFD by the condenser. All systems utilized typical three-phase, ball-bearing motors with constant-speed fan cycling control prior to the study. Each condenser included 4 to 10 fans and the number of fans on at any point in time were determined by the load the fans were required to meet. Table 1 includes descriptions of each device, the loads and temperatures served, if the VFD was in use during the study, and if it was discarded or not. For more details about the condenser specifications see Appendix A.

Table 1. Listing of the monitored stores, condensers, and what serve

Store	Unit Number	Serves	Low/medium/hi temp	VFD in use	Discarded
1	Rack A	Produce, deli, seafood	Medium	Yes	No
	Rack C	Dairy and meat	Medium	Yes	No
	Rack D North	Assorted frozen foods	Low	Yes	Yes
	Rack D South	Frozen meat	Low	Yes	Yes
2	Rack A East	Dairy & meat coolers	Medium	Yes	No
	Rack A West	Dairy & meat coolers	Medium	Yes	No
	Rack B East	Frozen food	Low	Yes	No
	Rack B West	Frozen food	Low	Yes	No
	Rack C	Produce, Deli	Medium	No	No
3	Protocol A	Beer cooler & frozen food	Mixed	No	No
	Protocol B	Frozen food	Low	No	No
	Protocol C	Dairy	Mixed	Yes	No
	Protocol D	Dairy	Medium	Yes	No
	Protocol E	Meat, Deli	Medium	Yes	No
	Protocol F	Meat	Low	Yes	No
	Protocol G	Bakery, produce	Medium	Yes	No
	Protocol H	Produce, meat, deli	Medium	Yes	No
	Protocol I	Produce, floral, seafood	Medium	Yes	No
4	Rack A	Meat and deli	Mixed	No	No
	Rack B	Dairy, bakery, produce, flowers	Mixed	Yes	No

This study included two types of condensers. One type, commonly referred to as a rack-system, has separate circuits that feed compressors and condensers. In contrast, a protocol system has a single circuit that feeds both the compressors and condensers along with some other smaller loads.

TESTING PROCEDURE AND DATA

To estimate the change in energy consumption from a VFD retrofit, we compared the power consumption between pre- and post-VFD retrofit. We expected the operating conditions to affect performance. Outdoor air temperature affects the ability of the condensers to reject heat from refrigeration fluids to rooftop environments. Therefore, we concentrated measurement efforts on condenser and compressor load and OAT, which is the dominant factor affecting condenser system load. Table 2 lists the data gathered.

Table 2. Monitored variables and equipment used.

Variable	Equipment used	Data collection interval	Equipment accuracy/source
Electric energy - condenser	eGauge 3000 electric meters with J&S current transformers sized to match circuit capacity	1-minute	Estimated at +/- 2% of measured values (including electric meter and CTs)
Electric energy - compressor	eGauge 3000 electric meters with J&S current transformers sized to match circuit capacity	1-minute	Estimated at +/- 2% of measured values (including electric meter and CTs)
Outdoor temperature	Rockford Airport temperature (˚F)	4-hour	Accessed from The Midwestern Regional Climate Center: https://mrcc.illinois.edu/CLIMATE/

The eGauge electric metering devices at each site were networked through a WiFi bridge to a cellular modem, allowing periodic downloading of the electrical data from our offices.

DATA COLLECTION

The study period ranged from mid-December of 2017 to mid-July of 2018 providing roughly two and one-half months for each of the pre- and post-retrofit periods. We remotely collected electrical energy data for each system through our communication links regularly throughout the study period.

We collected all power consumption data with eGauge devices, which included both rack and protocol-type refrigeration systems. The distinction between system types affected our data collection because rack-type condenser measurements resulted from direct measurements of the circuit supplying power to each individual condenser fan. Protocol-type condenser power measurements used current transducers to measure not only the power supplied to the condenser loads but also the power supplied to ancillary loads in the refrigeration system like lighting and door heaters from the sales floor coolers. We were able to isolate condenser loads in both system types but because the electrical circuit supplying power to the protocol systems serves additional loads, we do not have isolated power measurements to compressors from the protocol systems.

A few problems with data collection were encountered:

- We assigned status values to identify periods of operation for each system between events affecting performance, such as VFD retrofit, condenser coil cleaning, and including some changes that appeared with no known cause. This helped us identify and remove periods of results that affected condenser performance such as:
  - Several systems' power measurements appear to have been impacted by an unknown event in post-retrofit data. This was especially pronounced in the store 2 supermarket possibly due to spring road construction that generated a significant amount of deposition onto condenser coils. The condenser coils were cleaned during the study, and we included data both before and after cleaning on the assumption that coil cleanliness over the entire period approximated long-term variations.
  - Mechanical contractors performed system maintenance on some systems without reporting it, causing intermittent and unexplained periods of zero electrical energy

consumption. By requesting maintenance records for dates and times of maintenance we were able to identify these periods and remove them from the data set.

- A single site experienced a condenser fan motor failure. We discarded this data from the study.
- Failure of the remote Wifi connection to several eGauge electrical monitors prevented remote download for periods of time but no data was lost because of their ability to store data locally until remote connections were restored.

ANALYSIS APPROACH

The energy savings for this technology can be estimated by comparing average condenser energy use pre- and post-treatment at each of the experienced OATs, and then extrapolating to the typical outdoor air temperature distribution in a TMY. We collapsed condenser power measurements to 4-hour averages to remove the effects of short-term compressor and condenser fan cycling while preserving the ability to discern the effect of OAT on condenser performance. Both linear and non-linear regression models were required to complete this extrapolation, since not all OATs were experienced in both pre- and post-periods. The regressions assume a strong correlation between energy savings and OAT allowing us to estimate condenser energy consumption within the observed temperature range of the study. We then generalized to a typical year by using TMY weather data for each climatic zone of Illinois. This approach follows the principles in the uniform standards for VFD measurement and verification where condenser load is dependent upon OAT.[5]

Characteristic performance

Figure 1 shows a summary of performance for typical condenser systems. The plot includes daily 4-hour average power values in kilowatts (kW) on the vertical axis versus OAT in degrees Fahrenheit (ºF) on the horizontal axis. Red dots indicate the pre-retrofit relationship between power and temperature and the green dots indicate post-retrofit.

Several characteristics stand out. First, the response of power to temperature is non-linear for most systems before and after retrofit. Second, we observed different outdoor temperatures between pre- and post-retrofit. This is due to the months in which we conducted monitoring on each system. Pre-retrofit covered December to mid-April, while post-retrofit covered mid-April to mid-July. The two periods cover roughly the same number of months of monitoring but the variation in OAT differs. Third, there is a distinct separation between pre and post-retrofit data, with a significant decrease in power post-retrofit. Fourth, an unmistakable flattening of the post- retrofit data occurs above about 75 ºF. The inflection where this flattening occurs is the temperature at which the condenser fans all run at full power to maintain the required refrigerant pressure in the system. Below this maximum power point, system pressure is controlled to a constant by VFD modulation of condenser fan speed. Above this inflection point, condensers continue to reject heat but are unable to reject sufficient heat to maintain system pressure at the specified levels requiring, through increased load, that compressors deliver and maintain system pressure.

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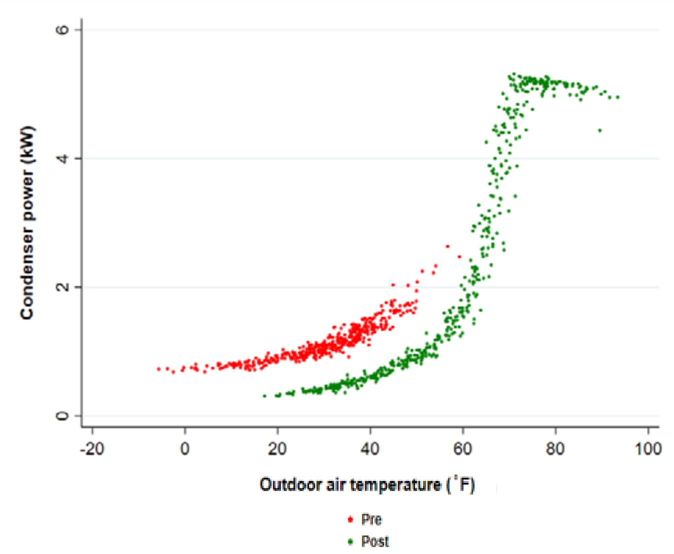
[5] Romberger, Jeff. 2017. *Chapter 18: Variable Frequency Drive Evaluation Protocol The Uniform Methods Project: Methods for Determining Energy-Efficiency Savings for Specific Measures*. Golden, CO; National Renewable Energy Laboratory. NREL/ SR-7A40-68574. https://www.nrel.gov/docs/fy17osti/68574.pdf

Figure 1. Characteristic performance pre-and post-retrofit

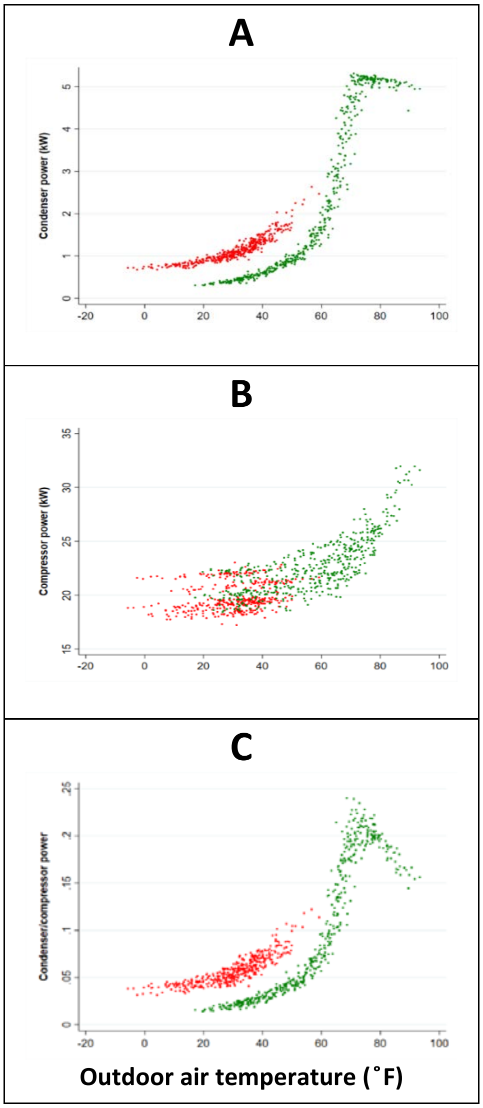


Above this inflection point any energy savings from VFDs no longer exists because the fans operate at 100% speed (and therefore power). In fact, above this point the condenser fan motor bypasses the VFD and runs through the contactors to avoid any inefficiency in the VFD circuitry at high frequency. Put another way, the VFDs are effectively no longer impacting the condenser and therefore no energy is saved beyond this point. There is some variation in where this inflection point occurred, due to the relative sizing between the condenser and the compressor it serves. We identified this inflection point by choosing the midpoint within a visually identified range of where maximum power occurs. This point varies by system but ranges from 69.5˚to 76.6 F.

Impact of system loading

We also used measurement of compressor power – as a proxy for load on the system – to investigate the impact of varying system loads on VFD savings. Figure 2 shows three panels: A, B, and C. Figure 2-A shows condenser power plotted over OAT, Figure 2-B shows just the compressor power versus OAT, and Figure 2-C shows the ratio of condenser power to compressor power, again versus OAT. We performed this visualization to investigate whether a significant amount of variance in the response of condenser power is a result of the load on the system. The ratio in Figure 2-C uses compressor power to normalize for the total system load. A simple visual comparison of Figure 2-A to Figure 2-C reveals that instead of collapsing the scatter of the data in both the pre (red) and post (green) periods, normalizing by the compressor power does not improve scatter and may even increase the scatter of the data. Failure to decrease the variance in either the pre- or post-retrofit power measurements suggests that the system load is not a strong driver of the power required by condenser fans, or the resulting savings of the VFDs. At the very least, it was not a helpful normalization parameter for this study.

Figure 2. Condenser, compressor and the ratio of condenser-to-compressor power



Correlation

As a result of the performance observations above, we relied solely on condenser power and OAT to calculate savings. To normalize for changes in OAT, we used regression analysis. We fit regression models to data using two distinct methods for some pre-retrofit systems; all post-retrofit systems used the same method.

These methods are demonstrated by Equations 1 to 5, which show differences in the models. Table 3, defines the meaning and units of the terms in those equations.

Pre-retrofit correlation Regression analysis allowed extrapolation beyond the OATs observed during the study period. Since we lacked the entire annual range of OAT for pre-retrofit values, we forced the pre-retrofit model through the maximum power or inflection point of the post-retrofit data; the pre and post would naturally converge at this point as described above. At temperatures above this point, VFDs are no longer modulating speed and no savings can occur. By extrapolating the regression model for pre-retrofit data to the same OAT range as post-retrofit data we were able to create a predicted value of power for pre- and post-retrofit for each temperature.

At one of the stores (store 3) condensers had a microchannel design and as a result one fan ran continuously even at very low temperature to avoid thermal shock to the microchannels. These condensers will never reach zero power, which is the reason for specifying a non-zero intercept in Equation 1. We used this equation where the minimum power is asymptotic to the lowest power consumption from running a single fan.

Pre-retrofit (store 3 only)

$$kW = \beta_0 + \beta_1 * e^{\beta_2 * OAT}$$

Equation 1

In contrast, Equation 2 allows the minimum power to be asymptotic to zero since without the microchannel design condenser fans *do* reach zero power at low temperatures. Equation 2 shows this by not explicitly including an intercept, or beta-naught while the rest of the model is identical.

Pre-retrofit

$$kW = \beta_1 * e^{\beta_2 * OAT}$$

Equation 2

In some cases, a minimum power point was clearly visible in pre-retrofit data. Here we found better success fitting a model to the data by using a segmented-linear regression show in Equation 3. An example of a segmented regression can be found in Figure 5 of Appendix B. There are two segments in this approach because below this 'breakpoint' temperature condenser power decreases with increasing OAT while above this temperature condenser power increases. We believe the negative slope above the 'breakpoint' temperature is due to decreasing air density and associated reduced fan power as ambient air temperature increases. We used this approach where we could visually identify a minimum power point. We identified the actual breakpoint based on the highest r-squared when choosing different 'breakpoints'.

Pre-retrofit (store 3)

$$\begin{aligned} kW &= \beta_0 + \beta_1 * OAT \quad for\ OAT \leq C \\ kW &= \beta_0 + \beta_1 * OAT \quad for\ OAT > C \end{aligned}$$

Equation 3

Post-retrofit correlation No observable minimum power point was discernable in any post-retrofit data so both post-retrofit models are non-linear. These models differ with respect to whether they are asymptotic to some non-zero power value because of the microchannel design at the store 3 store in Equation 4. Alternatively, Equation 5 shows the microchannel design where condenser power is not asymptotic to zero.

Post-retrofit (store 3 only) $$kW = \beta_0 + \beta_1 * e^{\beta_2 * OAT}$$ **Equation 4**

Post-retrofit $$kW = \beta_1 * e^{\beta_2 * OAT}$$ **Equation 5**

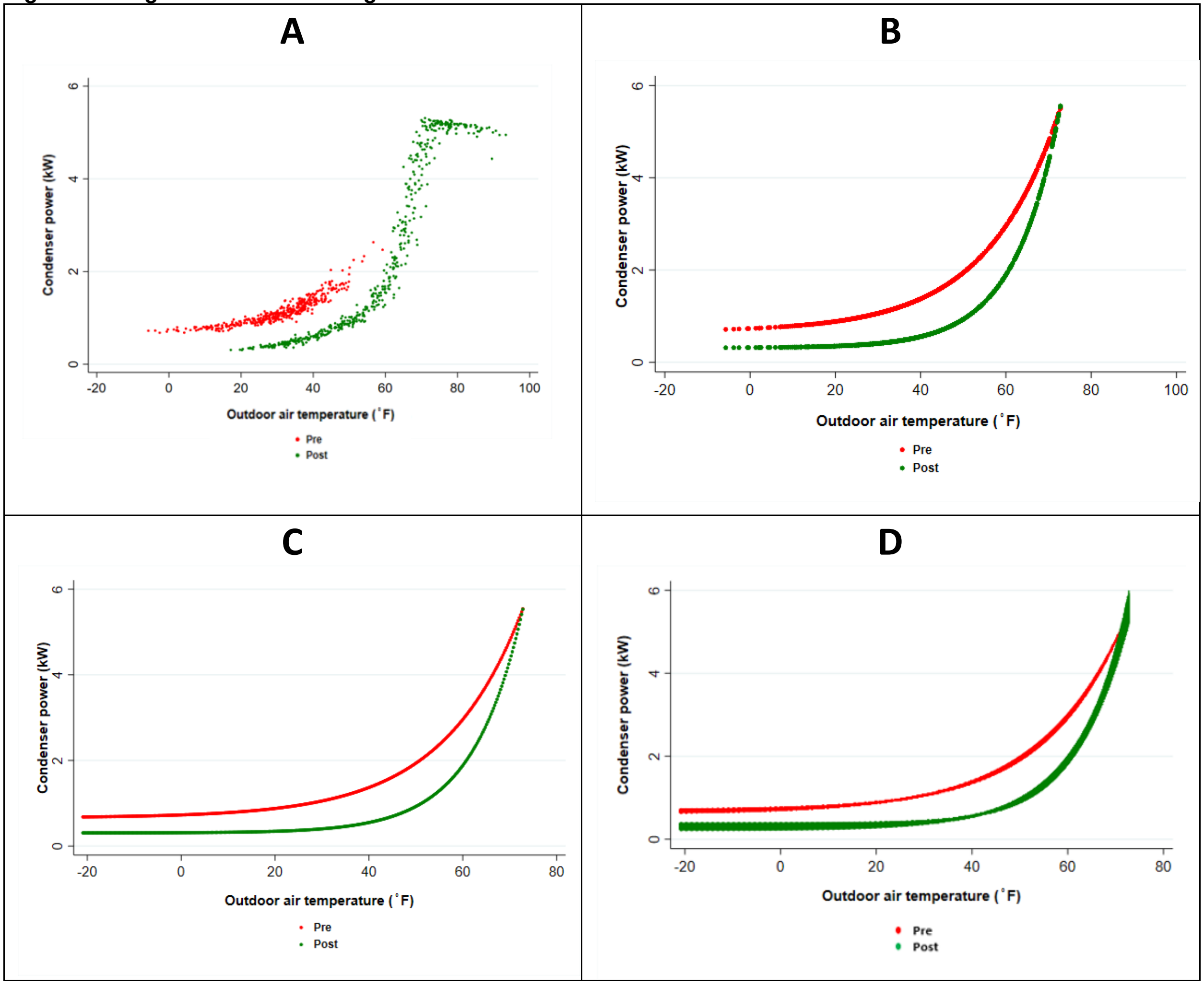
Table 3. Regression parameter definitions.

Designation	Meaning	Units
kW	1-minute average power observed	kW
β_0	regression constant	kW
β_1	Regression coefficient for effect of OAT for linear model OR base of the exponential model	Change in kW per change in degree F
B_2	Exponent term of the exponential model	Change in kW per change in degree F
e	Euler's constant	None
OAT	Outdoor air temperature	˚F

Figure 3 shows the progression of the modeling procedure we used to calculate savings. Figure 3-A shows the raw data after removing any anomalous periods of data for which we could not identify a cause (e.g. unexplained system shut downs). Figure 3-B shows predicted values from a regression model of that raw data; therefore, the lines are much smoother for both pre- and post-retrofit. These predicted values follow the temperature range of the observed data indicated by spotty predicted values near the ends of the temperature range. One important feature of Figure 3-B is that in contrast to Figure 3-A, the pre-retrofit data extends to the entire range and meets the maximum power point at the same point as the post-retrofit predicted values. This is a result of the extrapolation of the pre-retrofit model through the inflection temperature visible in post-retrofit data.

Figure 3-C shows a larger range of predicted values; this step used the full TMY range for this area of ComEd service territory in northern Illinois instead of the smaller range of observed temperature data. We then used a statistical procedure commonly referred to as “bootstrapping” the model coefficients to estimate the uncertainty in the results of the regression models. In this process we repeatedly sample with replacement from the distribution of the standard error of each coefficient. Figure 3-D shows the same model using predicted values from the bootstrapping procedure for pre- and post-retrofit data. The line width of both pre- and post- vary because they include 10,000 bootstrapped simulations of the model; width shows the resulting uncertainty in our extrapolation. For further review of the model results that include 10,000 simulations see Appendix B.

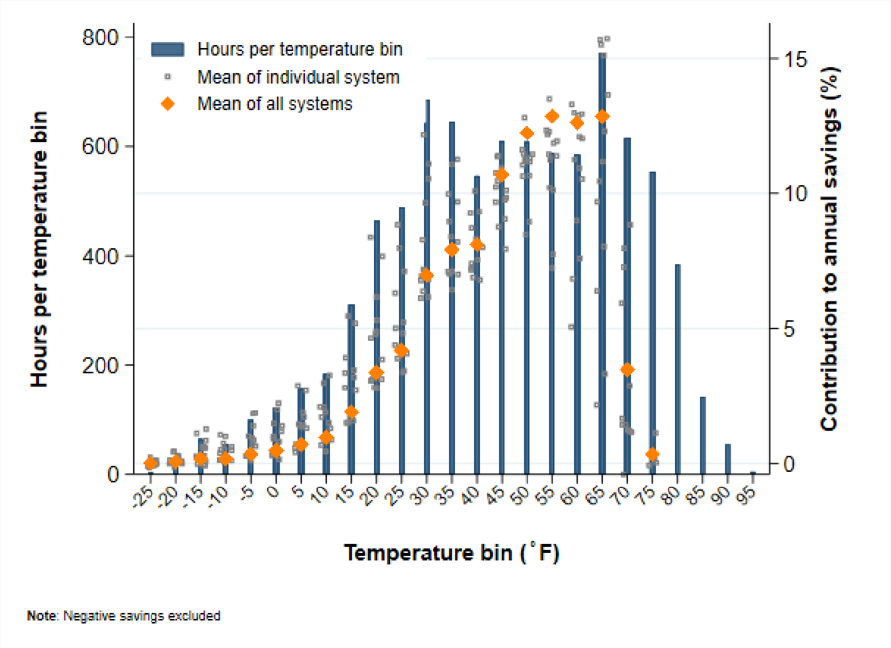
Figure 3. Progression of modeling



The area between the pre and post lines in Figure 3-D represents energy savings. To calculate that energy savings specifically, we separated both pre and post-retrofit power measurements into 5˚F temperature bins, then summed across bins for each condenser to get the total power saved for each system for each of the 10,000 simulations. At this point we multiplied the difference between pre- and post-retrofit in terms of power (kW) for each bin for each system by the number of hours in each bin to arrive at the energy (kWh) saved in each bin for each system across 10,000 simulations. The mean energy savings for each condenser across all simulations provides the mean annual energy savings.

Figure 4 shows energy savings distributed along the TMY temperatures binned in 5˚F increments on the horizontal axis. The number of hours in each temperature bin is shown along the left-hand vertical axis and the percentage contribution to annual savings on the right-hand vertical axis. Orange diamonds represent the mean percentage of savings across all sites that each bin contributes to total annual savings. Hollow gray squares show the different amount of savings for each condenser in the study for each bin. The only condenser with negative savings is excluded from Figure 4. Blue vertical bars show the number of hours for a TMY at a given bin. Each temperature bin demarcation represents the lowest temperature observed in that bin. For example, the 70 ºF bin includes all temperatures greater than or equal to 70 ºF and less than 75 ºF. There are no hours below -25˚F and none above 100˚F and the savings or orange diamonds are highest at mild temperatures and zero savings at temperatures above 75˚F. When operating above 75˚F post-retrofit, no system generated savings over pre-retrofit function.

Figure 4. Sources of savings by temperature bin



Note: Negative savings excluded

Most savings occur when OAT is between 45 and 75˚F. Savings also occur here because the highest frequency of hours of the year occur in those temperature ranges. The total energy savings result from the difference in energy consumption in each bin, multiplied by the total number of hours in each bin.

The 70 to 75˚F bins show markedly lower savings because we downrated the number of hours in the highest temperature bins. The inflection point described above generally fell in the middle of one of the bins for each condenser, so in each case that bin’s impact was downrated. We downrated by replacing the number of hours in the highest temperature bin with the difference of the highest temperature before maximum condenser power and the lowest temperature in that bin divided by the full five degrees in each bin. For example, if a condenser reached its maximum power at 72˚F and there are 100 hours in the bin from 70 to 75˚F, we would downrate the number of hours in the following way:

$$Downrate\ factor = \frac{72^{\circ}\mathrm{F} - 70^{\circ}\mathrm{F}}{5^{\circ}\mathrm{F}} = 0.4$$

RESULTS

The following figures and tables detail energy and dollar savings per year of operation, the total cost for installation, and a summary of the key performance indicators based on the 14 condensers in this analysis. Table 4 shows all condensers we used for analysis and what they serve.

Table 4. Final condensers analyzed in this report.

Store	Unit Number	Serves
1	Rack A	Produce, deli, seafood
	Rack C	Dairy and meat
2	Rack A East	Dairy & meat coolers
	Rack A West	Dairy & meat coolers
	Rack B East	Frozen food
	Rack B West	Frozen food
3	Protocol C	Dairy
	Protocol D	Dairy
	Protocol E	Meat, Deli
	Protocol F	Meat
	Protocol G	Bakery, produce
	Protocol H	Produce, meat, deli
	Protocol I	Produce, floral, seafood
4	Rack B	Dairy, bakery, produce, flowers

Energy savings

Energy savings resulting from variable frequency drive modulation are shown in Table 5. The table shows mean annual energy savings along with the 5th and 95th percentiles, for both total kWh saved and resulting percent savings. Finally, it also shows those savings normalized by condenser horsepower. Across all condensers, mean annual percent energy savings was 50 percent +/-9 percent (90% confidence). Savings range from 2,540 to -110 kWh/hp; mean savings was 1,480 kWh/hp.

Table 5. Annual savings

Store-Unit	Mean annual savings (kWh)	95th percentile savings (kWh)	5th percentile savings (kWh)	Mean annual savings (%)	95th percentile savings (%)	5th percentile savings (%)	Total hp	kWh savings/hp
3 Unit C	7,620	7,710	7,530	62	63	61	3	2,540
3 Unit D	12,460	12,630	12,290	60	61	59	6	2,080
3 Unit E	13,590	13,770	13,400	65	66	65	6	2,270
3 Unit F	5,540	5,690	5,390	38	39	37	6	920
3 Unit G	3,290	3,490	3,090	39	41	37	6	550
3 Unit H	-680	-490	-880	-7	-5	-9	6	-110
3 Unit I	8,320	8,510	8,120	39	40	38	6	1,390
2 Unit A	19,420	20,060	18,780	72	74	69	9	2,160
2 Unit A2	10,520	11,340	9,710	45	49	42	9	1,170
2 Unit B	11,020	11,610	10,430	57	60	54	9	1,220
2 Unit B2	17,960	18,640	17,270	66	68	64	9	2,000
4 Unit B	14,650	15,570	13,760	63	67	59	7	2,090
1 Unit A	20,890	23,020	18,680	45	50	41	15	1,390
1 Unit C	18,470	19,480	17,380	49	51	46	18	1,030

The single system with negative savings did experience positive savings at lower temperatures. After a site visit to investigate, the cause remains unknown. Appendix B includes a full account of the models that produced these results.

Illinois has five different degree-day zones. Since condenser fan power consumption depends on OAT, savings may be different in different parts of the state. Table 6 shows average savings per horsepower for each zone. Although we collected data and calculated savings only for Rockford—closest to the store locations of this study—TMYs specific to each degree-day zone allow extrapolation to a generalized year in each zone. At first glance the results across climate zones may seem to vary without pattern. Table 6 also shows the confidence interval for each, which suggests they have no statistical difference from each other (the confidence intervals overlap between zones). This reflects the fact that most of the energy savings occur in the shoulder seasons, and the degree to which climate zones contain more extreme summers or winters has little effect on results.

Table 6. Savings by degree-day zone for Illinois

Zone	Mean kWh savings/hp	Confidence Interval (90%)
1 (Rockford)	1,480	+/-330
2 (Chicago)	1,500	+/-330
3 (Springfield)	1,430	+/-300
4 (Belleville)	1,430	+/-320
5 (Marion)	1,480	+/-310

Economic results

The estimates in Table 7 include the total installed cost along with the total annual energy cost savings, both normalized by the horsepower of the condenser. The total installed cost per horsepower includes the cost of equipment and labor together and ranges from about $800 to about $2,000. We assumed a $0.10/kWh cost of electricity to calculate the total annual savings per horsepower, which ranges from about $250 to about $50 with the system with negative energy savings showing negative dollar savings. The limited size of this field study does not allow a definitive analysis of the economic benefits of VFD retrofits because of the lack of variation in installers, devices, manufacturers, and the timeframe over which benefits accrue.

Table 7. Installed cost and annual savings summary

Store-Unit	Total hp	Total installed cost/hp	Total annual savings/hp
3 Unit C	3	$1,970	$250
3 Unit D	6	$1,190	$210
3 Unit E	6	$1,190	$230
3 Unit F	6	$1,190	$90
3 Unit G	6	$1,190	$50
3 Unit H	6	$1,190	$-10
3 Unit I	6	$1,190	$140
2 Unit A	9	$900	$220
2 Unit A2	9	$900	$120
2 Unit B	9	$900	$120
2 Unit B2	9	$900	$200
4 Unit A	7	$2,080	$210
1 Unit A	15	$780	$140
1 Unit C	18	$810	$100

Table 8 summarizes the overall quantitative results from the analysis, averaged across all condensers. As shown in Table 8, the estimated annual energy saved is 1,480 kWh/hp +/-330kWh (90% confidence). The average annual energy cost saved is $150/hp +/-$30 (90% confidence). The average total cost of installation is $1,170/hp and +/-$170 (90% confidence) across all condensers.

Table 8. Key performance indicators

Key performance indicator	Amount/hp	90% confidence interval
Estimated annual kWh saved	1480 kWh	+/-330
Estimated annual dollars saved	$150	+/-30
Cost of installation	$1,170	+/-170

Overall, we estimate positive annual energy and cost saved. Including only costs saved from energy savings and ignoring non-energy benefits (see those below) the simple payback for the retrofit of an average VFD in this study is about eight years. This payback is based on the current cost of technology and without incentive payments. Incentives provided by ComEd as well as reduction in cost – as retrofits become popular – both have a significant potential to reduce this payback.

Lessons learned and non-energy impacts

We qualitatively investigated the impact of retrofitting the supermarkets in this study in three main ways: how installation may affect a store from the point of view of the installer, how VFDs affect refrigeration systems during operation, and any impacts on the stores themselves. The lessons learned are summarized below.

INSTALLATION

- During the monitoring period there was a single instance where VFD installation affected the direction of rotation for the condenser fans. The VFDs themselves were not responsible for a change in the direction of the fan rotation. The problem resulted from simple miswiring. Installers must be certain the fan rotation direction is correct. Incorrect installation of the VFD can result in incorrect fan rotation which can be diagnosed as larger than normal current draw and burnt motors, both of which cause increased costs. Typical maintenance schedules should fix any miswiring that results in incorrect fan rotation, but this will likely go undiagnosed for months or longer between maintenance. System monitoring could correct these issues faster but is currently atypical.
- Commissioning systems with retrofitted VFDs is not substantially different from commissioning systems without them. Points to check should include amp draw, rotation, and head pressure.
- Mechanical contractors and previous research suggest maintenance benefits where condenser fans have been retrofitted with VFDs. These benefits include:
    - The ability of VFDs to limit fan speed during operation may increase motor life and result in fewer maintenance trips for motor burnout during the life of condenser fans. This results from general benefits of VFDs to motors including a much softer startup and operation at lower speed throughout service.[6] This benefit would certainly be relevant to condensers, where the fans cycle on and off frequently.
    - Installing VFDs makes cleaning coils easier because a technician can simply reverse the fan rotation and blow the dust or debris out of the coils.
    - Microchannel condensers have at least a single motor that always remains on to keep unit temperature more consisting, reducing expansion and contraction. Operation with VFDs will minimize the power of the single fan during low temperatures.

IMPACT TO STORES

- VFD operation does not seem to affect store operation in any significant way other than expected benefits of saved energy.
- Store operators suggest the importance of conducting installation when stores are not at peak occupancy. Any interruption to refrigeration during these times is especially detrimental to store operation and sales.
- Mechanized delivery aids installation since much of the work is conveying the VFDs to the roof (when installed on the roof). This also aids more timely installation, which reduces the risk of refrigeration mishaps and other issues that may affect store operation.
- Much of the cost of these retrofits is in the labor involved in installation. As a result, installing VFDs at supermarkets with many condensers appears to have more value because of economies of scale for installation.

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[6] US Department of Energy (DOE). "A sourcebook for industry: Improving motor and drive system performance." (2008).

Program recommendations

Results from this research demonstrate that energy savings from retrofitting refrigeration condenser fans with VFDs are robust and consistent enough for inclusion in prescriptive rebate programs. A TRM work paper has been submitted with the results from this research and was accepted for inclusion in version 7 of the TRM. Therefore, the measure should be readily added to virtually any of ComEd's programs (and other similar electric utilities, for that matter).

The measure would of course fit well in the prescriptive offerings for either refrigeration or VFDs. It is worth other programs being aware of the measure though. This includes retro-commissioning, where several building types, not just supermarkets, will encounter refrigeration systems. It also includes both small business and chain store programs, which often include many food-service and food-sales building types. Where this measure is included in these programs, program managers should address the qualitative lessons learned in the section immediately above with requirements and guidance in their program offerings.

Finally, the measure is also applicable to some industrial customers and programs. Care should be taken as refrigeration systems get larger – industrial scale refrigeration for something like cold-food processing may recognize a different energy savings profile than a supermarket. But smaller and medium sized industrial refrigeration systems may be applicable.

The measure does not have applicability to new construction, because it is now required by code in new refrigeration systems.

CONCLUSIONS

Our study found significant savings from retrofitting supermarket condensers with VFDs. This technology is applicable to cold climates and should be considered for inclusion in utility energy efficiency programs in Illinois. Based on estimated energy savings from 14 analyzed, we conclude that VFDs retrofitted onto condenser fans can save 50 percent, +/-9 percent of the annual energy consumed without retrofit. This represents annual savings of 1,480 kWh/hp +/-330, and corresponding energy cost savings of $150/hp+/-$30. The average cost of installation is $1,170 +/-$170 (all metrics reported at the 90% confidence level).

There are multiple lessons learned that are not included in savings and cost figures. Proper installation and commissioning of VFDs after retrofit is important for the short and long-term viability for energy savings. Although unquantified here, VFD retrofits may have additional benefits of decreasing maintenance costs, largely through extended lifespan of motors and decreased labor to wash condenser coils. Store owners may see benefit from economies of scale in installation; since labor is an important factor in retrofit cost, stores with more rather than fewer condensers may have additional value to store owners. Retrofitting condenser fans with VFDs in commercial refrigeration systems can be considered an appropriate technology for electrical energy savings in cold climates should be included in in prescriptive rebate programs.

APPENDIX A

Table 9. Store 3

Unit Number	Condenser Model	Voltage	# of Fans	hp	Split	Fan FLA	Total FLA	KE2 Fan Part #
Protocol A	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol B	MXC-02	208/3/60	2	1.5	NO	6	12	KE2 FAN-022-E196-000-000
Protocol C	MXC-02	208/3/60	2	1.5	NO	6	12	KE2 FAN-022-E196-000-000
Protocol D	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol E	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol F	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol G	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol H	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000
Protocol I	MXC-04	208/3/60	4	1.5	NO	6	24	KE2 FAN-042-E300-000-000

Table 10. Store 1

Unit Number	Condenser Model	Voltage	# of Fans	hp	Split	Fan FLA	Total FLA	KE2 Fan Part #
Rack A	CDS-122	480/3/60	10	1.5	NO	2.7	27	KE2 FAN-104-C310-360-000
Rack B	CDS-054	480/3/60	4	1.5	NO	2.7	10.8	KE2 FAN-044-C175-000-000
Rack C	CDS-136	480/3/60	12	1.5	NO	2.7	32.4	KE2 FAN-124-C380-000-000
Rack D North	CDS-090	480/3/60	8	1.5	NO	2.7	21.6	KE2 FAN-084-C310-000-000
Rack D South	CDS-090	480/3/60	8	1.5	NO	2.7	21.6	KE2 FAN-084-C310-000-000

Table 11. Store 2

Unit Number	Condenser Model	Voltage	# of Fans	hp	Split	Fan FLA	Total FLA	KE2 Fan Part #
Rack A East	RCS080VE	230/3/60	6	1.5	NO	5.4	32.4	KE2 FAN-062-E400-000-000
Rack A West	RCS080VE	230/3/60	6	1.5	NO	5.4	32.4	KE2 FAN-062-E400-000-000
Rack B East	RCS080VE	230/3/60	6	1.5	NO	5.4	32.4	KE2 FAN-062-E400-000-000
Rack B West	RCS080VE	230/3/60	6	1.5	NO	5.4	32.4	KE2 FAN-062-E400-000-000
Rack C	RCS080VE	230/3/60	8	1.5	NO	5.4	43.2	KE2 FAN-082-E560-000-000
Rack D	RCS080VE	230/3/60	6	1.5	NO	5.4	32.4	KE2 FAN-062-E400-000-000

Table 12. Store 4

Unit Number	Condenser Model	Voltage	# of Fans	hp	Split	Fan FLA	Total FLA	KE2 Fan Part #
Rack A	HACVBI-14408M	460/3/60	14	0.5	NO	1.2	16.8	KE2 FAN-144-A230-000-000
Rack B	HACVI-14410M	460/3/60	14	0.5	NO	1.2	16.8	KE2 FAN-144-A230-000-000
Rack C	HACVI-10410M	460/3/60	10	0.5	NO	1.2	12	KE2 FAN-104-A175-000-000

APPENDIX B

Figure 5. Store 3 condenser C pre- and post-performance

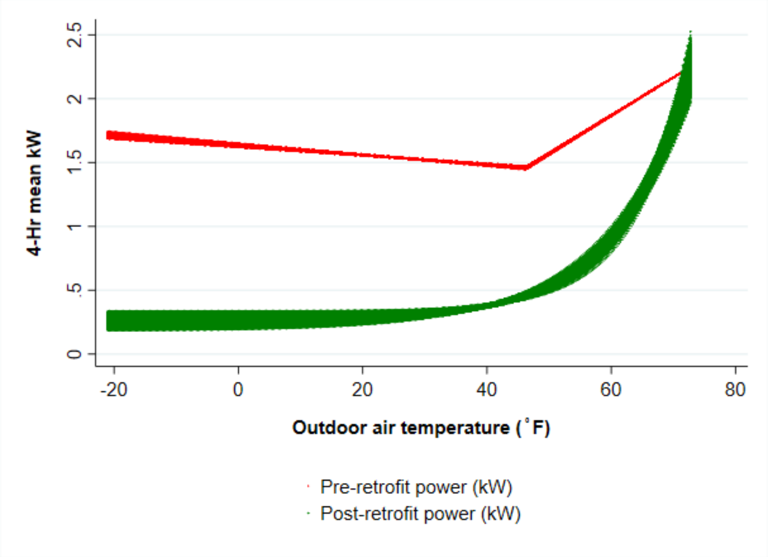

Figure 6. Store 3 condenser D pre- and post-performance

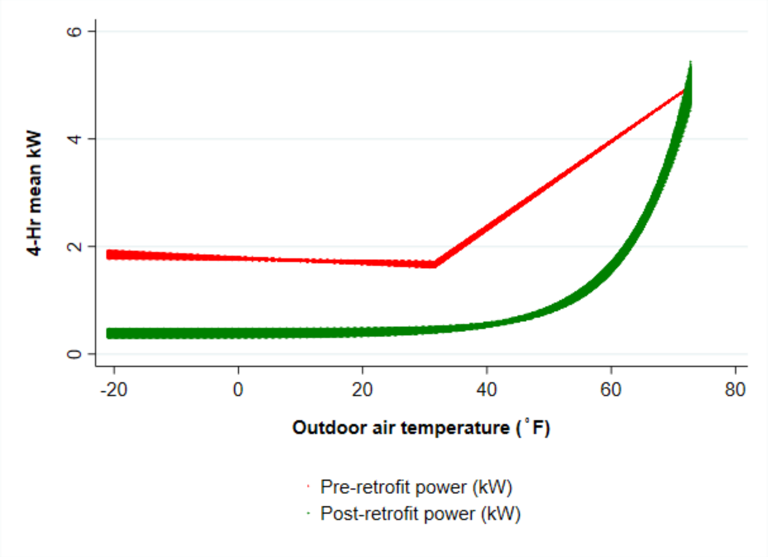

Figure 7. Store 3 condenser E pre- and post-performance

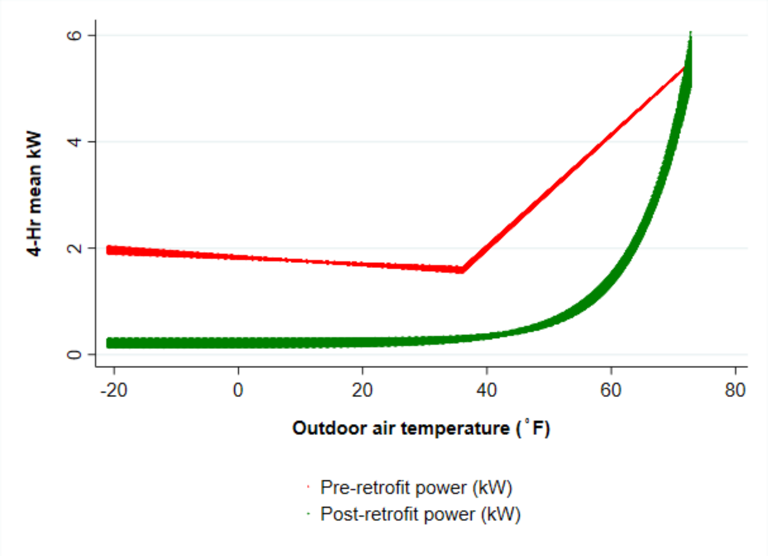

Figure 8. Store 3 condenser F pre- and post-performance

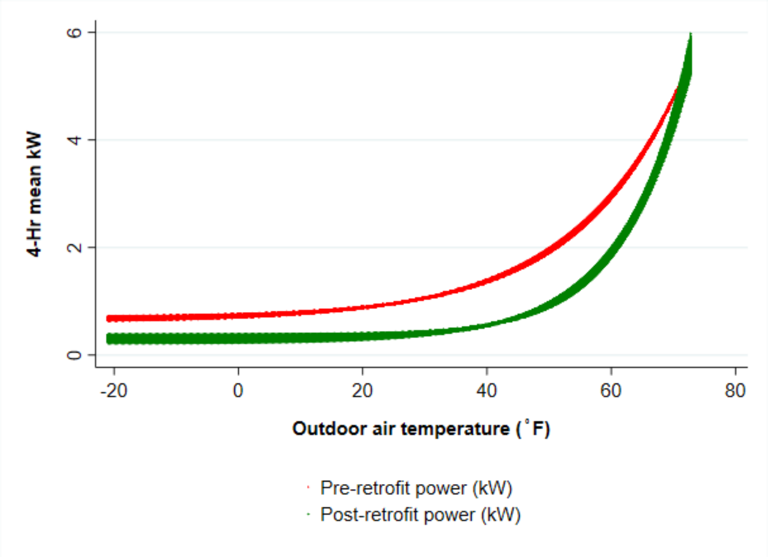

Figure 9. Store 3 condenser G pre- and post-performance

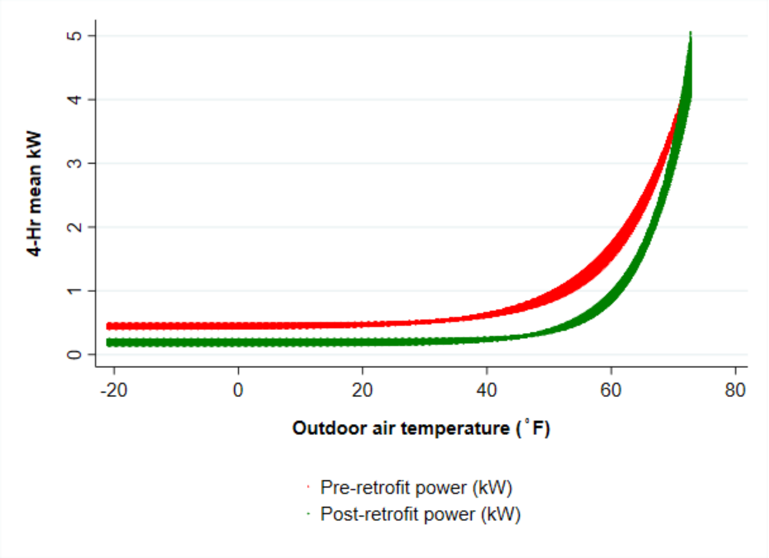

Figure 10. Store 3 condenser H pre- and post-performance

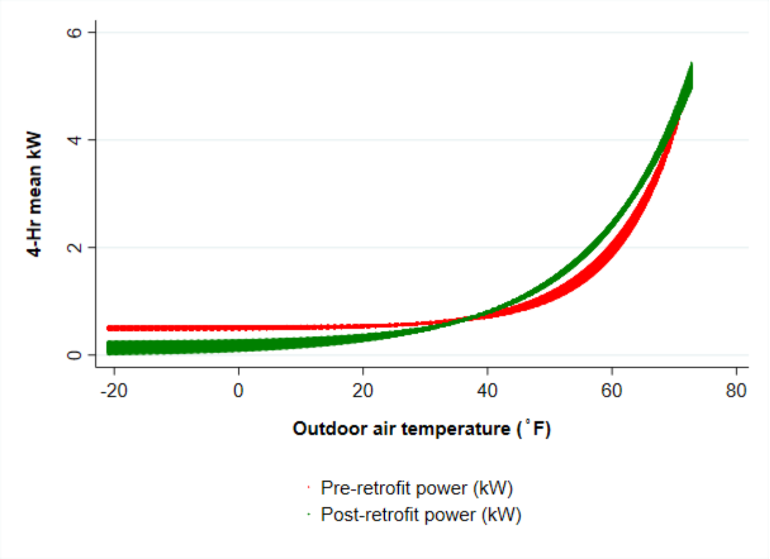

Figure 11. Store 3 condenser I pre- and post-performance

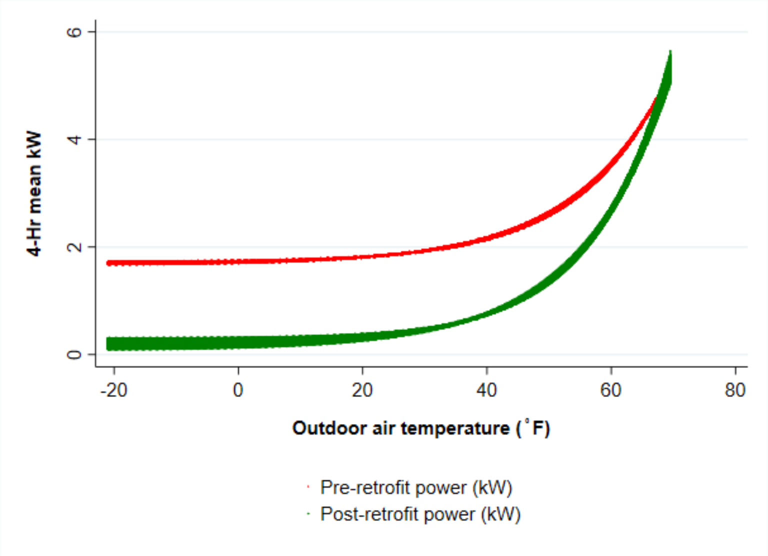

Figure 12. Store 2 condenser A (east) pre- and post-performance

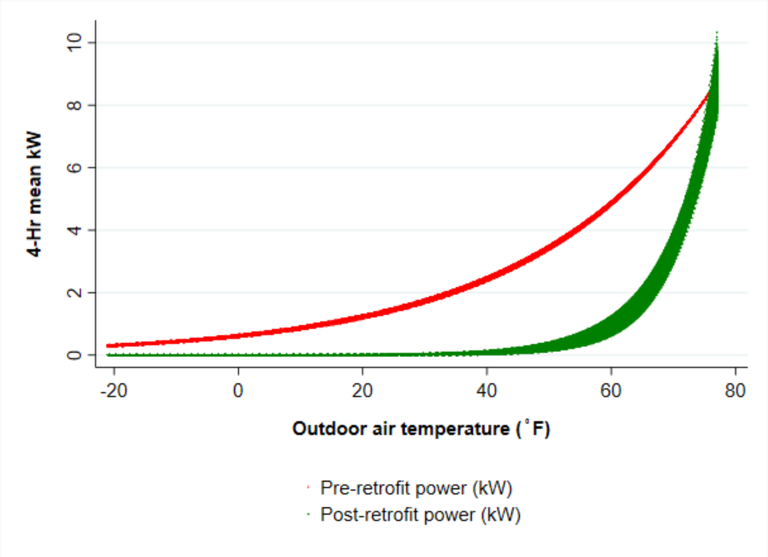

Figure 13. Store 2 condenser A (west) pre- and post-performance

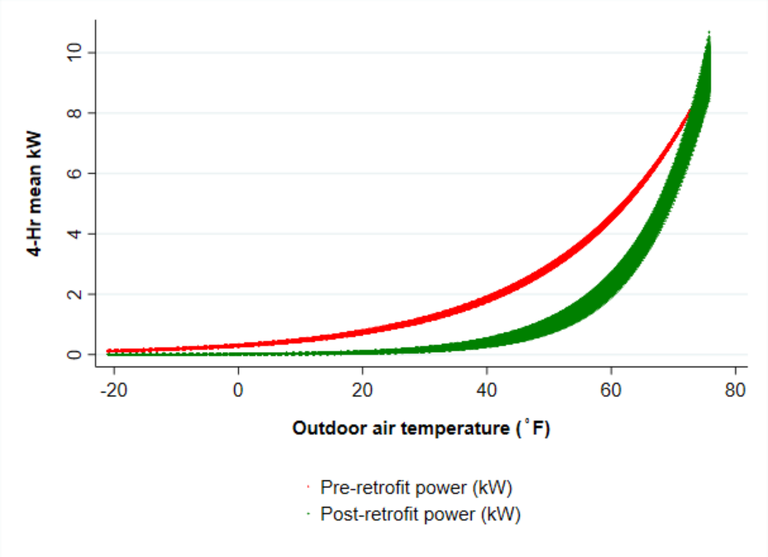

Figure 14. Store 2 condenser B (west) pre- and post-performance

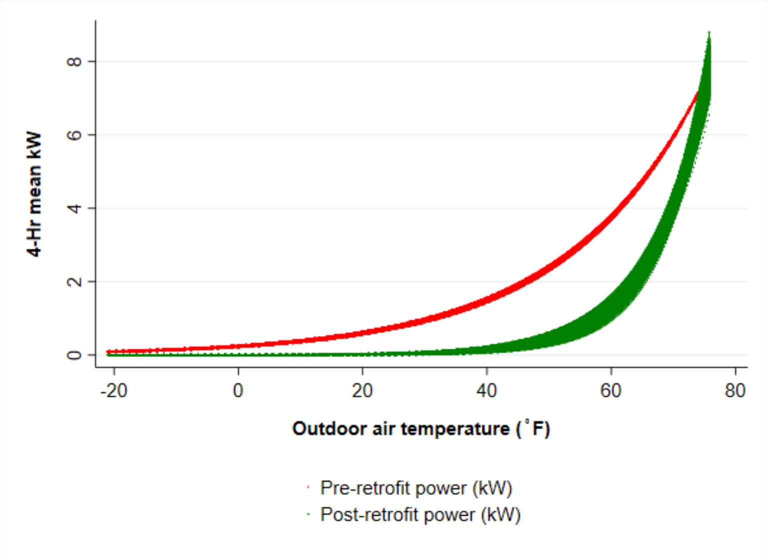

Figure 15 Store 2 condenser B (east) pre- and post-performance

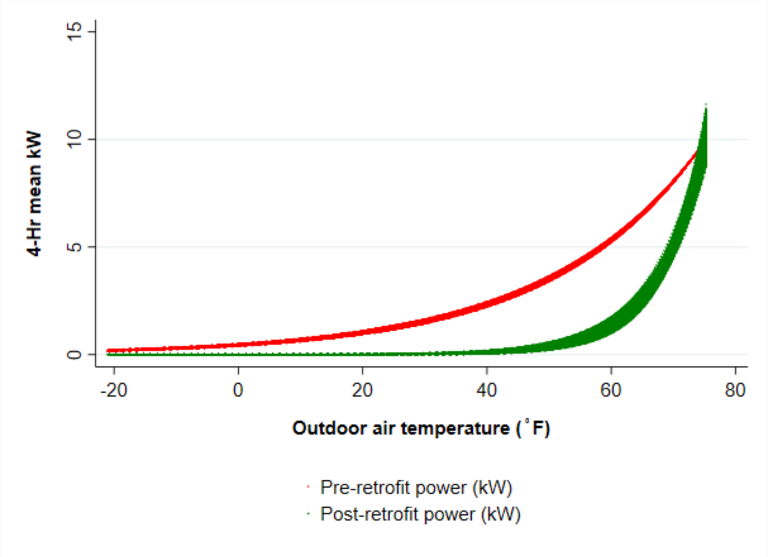

Figure 16. Store 4 condenser B pre- and post-performance

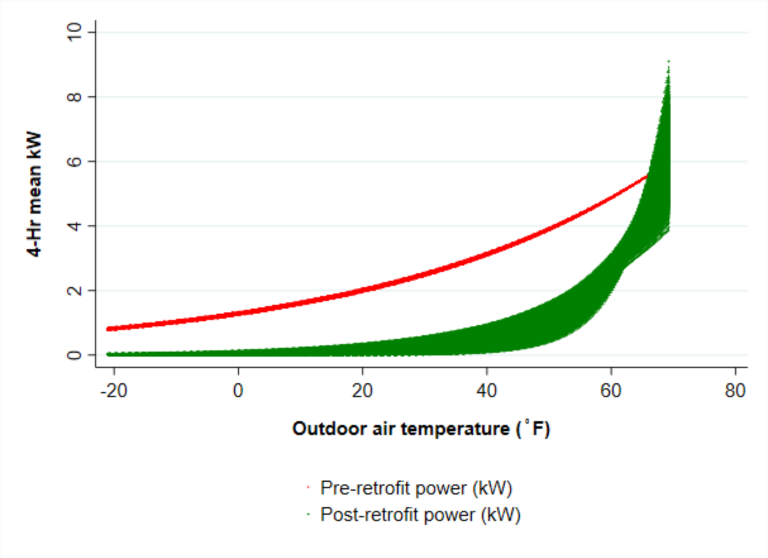

Figure 17. Store 1 condenser A pre- and post-performance

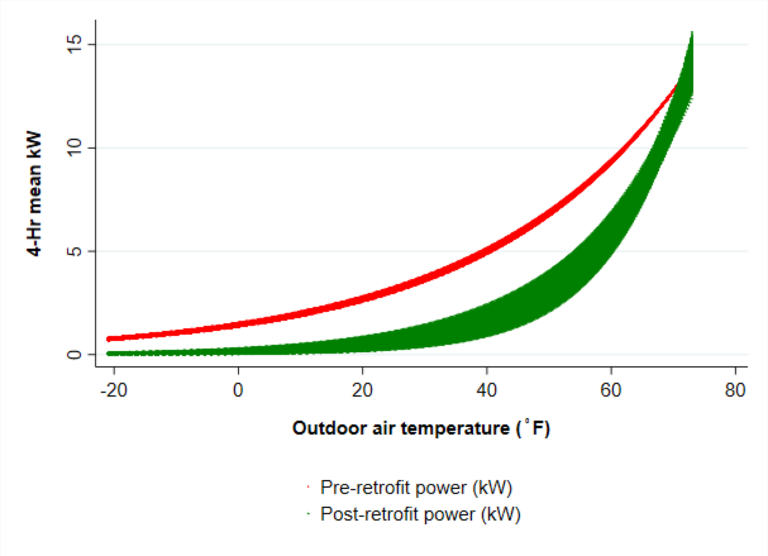

Figure 18. Store 1 condenser C pre- and post-performance