Industrial Refrigeration Projects:

Challenges and Opportunities for Energy Efficiency

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ABSTRACT

Industrial refrigeration energy efficiency projects are challenging to tackle due to their dynamic configuration, complex operations, and multiple system interactions. The key components that make up industrial refrigeration systems are compressors, evaporators, condensers, and controls. These components have unique input parameters such as suction pressure, discharge pressure, and cooling demand, all driven by a highly inconsistent external variable: weather. To achieve the best operating efficiencies, it is important that facility managers understand these components and their impact on the overall system.

The objective of this paper is to present case studies that highlight industry best practices and their impact on energy efficiency, as well as to identify potential areas for improvement and the challenges in implementing them. The case studies will highlight projects in Ohio and Nevada—two geographic areas with distinctly different weather and climate patterns.

The presentation of these two case studies is intended to provide important insights to facility managers as they consider future projects. One example of an area for improvement that will be explored in depth is control upgrades. The solutions for addressing this challenge, and others, are illustrated through discussions of the referenced case studies. The authors provide recommendations for industry best practices that may be applied to future technical reviews of industrial refrigeration projects. Additionally, findings are extrapolated to other technology and market segments, as relevant. Recommendations from this paper are intended to drive reduced energy use intensity and improve operational productivity.

Introduction

Both developed and developing countries around the world utilize industrial and large commercial refrigeration systems. Application of these systems includes food preservation, cold storage, and heat removal from industrial processes applications. In this paper, industrial and large retail food store applications are presented as case studies. The results and recommendations for the two applications are provided as a reference for future projects.

Refrigeration consumes about 381 trillion Btu (about 11%) of the total electricity used by all commercial buildings nationwide (U.S. EIA 2003) while large supermarkets and grocery stores have one of the highest electric usage intensities in commercial buildings at 278 kBtu/ft^2 per year (U.S. EPA 2008). Depending on the design and system controls of a refrigeration system, it is most likely that peak energy consumption of a large retail food store coincide with electrical utilities have their highest demand for electricity. Typically, a refrigeration system produces the desired result of preserving food, but may not function in a way to maximize its optimized conditions or desired operating strategies.

Industrial refrigeration systems come in myriad sizes, configurations, and arrangements. This system component diversity is one of the biggest challenges for industrial refrigeration system designers and operators. Oftentimes, each component is produced by a different manufacturer. The effects that each component has on the others can significantly decrease or increase the system's performance. This paper explores industrial refrigeration system optimization and control, including how to maximize the overall efficiency of a refrigeration system's operation with a focus on the key components including the evaporator, compressor, condenser, and control device. A schematic of a typical basic refrigeration system is shown below.

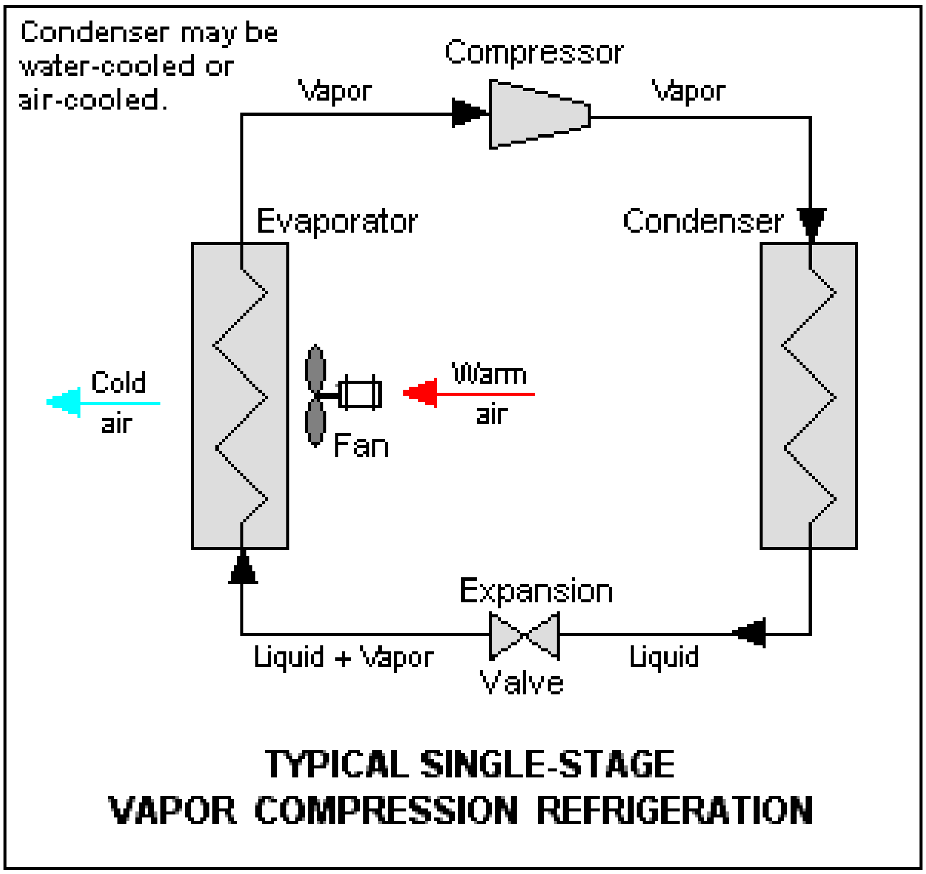


Figure 1. A schematic of A Basic Refrigeration System. *Source:* http://en.wikipedia.org/wiki/Vapor-compression_refrigeration

Key System Components

Compressor

A compressor draws the low-temperature and low-pressure vapor from the evaporator via the suction line. It then compresses the vapor and the temperature increases. This process of transforming the vapor from a low-temperature vapor to a high-temperature vapor increases the pressure. Next, the compressor releases the vapor into the discharge line.

The refrigeration industry commonly uses screw and reciprocating compressors. Screw compressors are compact and create less noise when compared to reciprocating compressors. At full load, screw compressors are more efficient, but at part load, reciprocating compressors are more efficient. Because compressors perform the work in a refrigeration system, they typically consume most of the required system energy. As a result, efficiency measures that reduce compressor power loads are a focus of this paper.

Condenser

The condenser extracts heat generated during the refrigeration cycle and pumps it into the outside air. Fans mounted above the condenser unit draw air through the condenser coils. The temperature of high-pressure vapor determines the temperature at which condensation begins. The high-pressure vapor within the condenser is cooled to the point where it becomes a liquid refrigerant. The liquid refrigerant then flows from the condenser into the liquid line. Refrigeration systems use three common types of condensers: air-cooled, evaporative, and water-cooled.

Control Device

A control device, such as an expansion valve, releases high-pressure liquid refrigerant into a low-pressure liquid/vapor mixture that then feeds into the evaporator. The expansion valve controls the refrigerant flow entering the evaporator based on the amount of superheat generated by the gas leaving the evaporator. The device controls the mass flow of refrigerant entering the evaporator so that it is equal to the rate at which it can be completely vaporized in the evaporator by the absorption of heat. The expansion valve functions to keep the evaporator actively cooling while preventing liquid from returning through the suction line to the compressor.

Evaporator

The evaporator removes unwanted heat from the refrigerated space or the product via liquid refrigerant, which boils at a low pressure. The rate at which the heat is absorbed from the product to the refrigerant and the rate at which the low-pressure vapor is removed from the evaporator by the compressor determines the pressure. During the heat transfer process, the temperature of the liquid refrigerant must be lower than the temperature of the product or space being cooled. Doing so allows the compressor to draw the liquid refrigerant from the evaporator via the suction line. The liquid refrigerant is in vapor form when it leaves the evaporator coil. During the refrigeration process, frost builds on the evaporator coils because they operate below the freezing point, so the frost must be removed periodically from the coils to prevent accumulation, which blocks airflow and degrades performance. Common defrosting methods include the use of hot gas, hot water, and electric heat.

Case Studies

Industrial Refrigeration System-Ohio

The first case study examines a food manufacturing plant in Ohio, located in climate zone 5A, cool-humid, (ASHRAE 2010). The plant processes bakery products. The plant area is about 168,000 square feet with production schedules from 10 pm Sunday to 10 PM Friday year round, excluding holidays. The refrigeration system uses ammonia as the refrigerant, and is equipped with four rotary screw compressors (one booster, one swing, and two high-stage machines) and two evaporative condensers. The total installed compressor's capacity is 909 tons. It services the blast freezers, cold storage warehouse, process cooling, and space-cooling loads. The loads are served using two primary suction loops and a fixed operating condenser pressure.

The facility made several infrastructure upgrades and energy-efficient retrofits designed to minimize its energy consumption. Upgrading the plant's condensers with new equipment outfitted with floating head pressure controls on the supply side, and replacing the shell and tube heat exchanger with a plate and frame-heat exchanger on the demand side were two elements of the project. The key energy efficiency measure decreased condenser pressure and based the operation on outside air conditions instead of fixed operation conditions. The EEM is addressing the condenser infrastructure improvement, but it has the greatest impact on the compressor power. Without the floating head pressure control, the condenser pressure was operated between 155 pounds per square inch gauge (psig) to 135 psig (summer to winter) controlled based on manual setpoints and, with the implementation of the EEM, the operating pressure ranged between 140 psig to 125 psig (summer to winter) automatically varying with weather. On average, the compressor differential pressure is reduced by 10 -15 psig.

As a result of installing floating head pressure control systems, the plant reduced the condenser pressure. This process ultimately reduced the load on the compressors, particularly during winter and transition months. The results of the analysis indicate that the compressor efficiency improved approximately 38% (a reduction from 1.37 kW per ton to 0.84 kW per ton) with about 29% reduction in the refrigeration energy consumption. For the same load conditions, it is possible to achieve up to 11% additional reduction in energy consumption. The plant could achieve these savings by incorporating the compressor controls and sequence upgrades, ensuring that multiple compressors do not operate in partial-load conditions.

Table 1. Summary of project findings

Baseline Annual Energy Use (kWh)	Proposed Annual Energy Use (kWh)	Annual Energy Savings (kWh)
2,540,316	**1,790,008**	**744,308**

Large Retail Food Refrigeration System-Nevada

This case study examines a 97,000-gross-square-foot new construction supermarket project in Las Vegas, Nevada. The building owner believes that being a part of the southern

Nevada community means more than simply having a grocery store in the city. Therefore, he established the “Green Initiatives” program that includes details on setting sustainability goals, developing action plans, and implementing energy efficiency and renewable energy for his stores. Knowing that refrigeration is a large contributor to the world’s energy consumption, the owner wanted to decrease the store’s overall energy consumption by implementing energy-efficient refrigerated and frozen equipment measures.

Oftentimes, facilities can easily achieve energy savings by incorporating energy efficiency technologies in the project design, rather than through retrofit projects. This impact is particularly true for new construction projects. To achieve the owner’s goals, the design team included an architect, engineers, an energy consultant, and a local utility representative who worked together early in the conceptual design phase and continued through building commissioning. Extensive whole-building energy modeling and lighting computer simulations were conducted throughout the process, which included integrating energy-efficient and renewable energy technologies into the building design. The team used DOE-2.2R, building simulation software for Refrigeration system to perform energy use and simulate behavior of the refrigeration system operation and its performance. The DOE-2.2R utilizes comprehensive simulations procedure, an hour-by-hour analysis to carry out energy consumptions for both baseline and as-built designs.

Efficient refrigeration systems are developed through proper design, the use of premium-efficiency equipment, the installation of appropriate system controls, and regular maintenance. Therefore, the design team set challenging goals for the project by striving to implement the latest information on energy efficiency technologies in refrigeration systems for the large commercial supermarket industry. Energy efficiency measures implemented in this project design included:

- Optimized compressor sequencing with variable frequency drives (VFDs)
- Moderately oversized condensers
- High-efficiency display cases with premium-efficiency electronically commutated motors (ECMs)
- Floating head pressure following wet-bulb temperature (WBT) approach
- Floating suction pressure
- High-efficiency lighting fixtures and controls

Designed to meet the needs of the Las Vegas valley for many years to come, this large grocery store incorporated green building design to minimize energy consumption and reduce greenhouse gas emissions. The design also yielded a variety of other benefits, including lower monthly utility bills and better air quality, which improves the quality of life for individuals and the community.

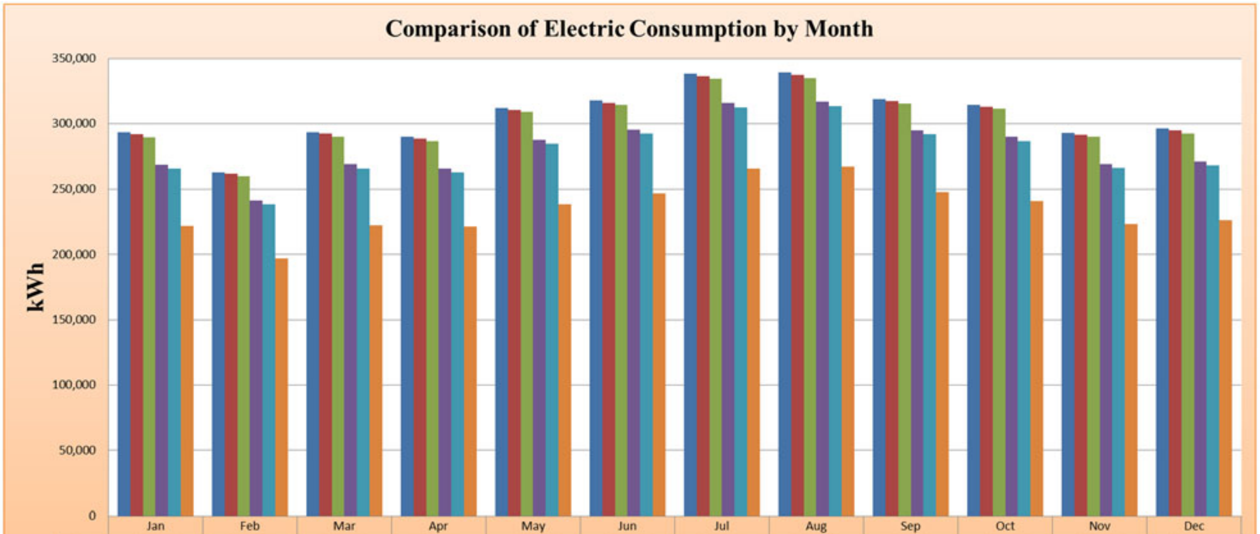
The results of the analysis are summarized in the tables and figures below. Table 2 presents a summary of the simulation results from DOE-2.2R. The principal features of the baseline refrigeration system model are compliant with ANSI/AHRI 2007/LEED 2009 for Retail. Improvements to this model were then made to reflect design enhancements to the refrigeration system components, including the compressor, evaporator, condenser, and refrigerated display cases. In addition to the refrigeration system controls, the lighting and daylight harvesting systems were also incorporated into the as-proposed building. These input parameters are given in Table 3. Using the Typical Meteorological Year (TMY3) weather data for Las Vegas, the annual energy performances over the long term averaged are then used to determine energy consumptions between the code-compliant benchmark building and the as-designed building. The result illustrates that the as-designed building achieved approximately 23.2% (851,722 kWh/yr) in annual electric energy savings per year as compared to a minimally code-compliant building. More detailed results are shown in Figure 2 below.

Table 2. Summary of project findings

Baseline Annual Energy Use (kWh)	Proposed Annual Energy Use (kWh)	Annual Energy Savings (kWh)
3,669,848	2,818,126	851,722

Figure 2 reports the total electric energy consumptions by month. The total of six simulations was done beginning with the minimum code-compliant baseline model, Run 1. Each run was then incrementally incorporated into the features of the previous run. Note that the intermediate runs are provided for informational purposes to assess the relative impact of each system's components. Calculations are finalized only between the ANSI/AHRI/LEED for Retail base and the final run (Run 6), which reflects the cumulative impact of all refrigeration system, lighting, and daylight harvesting upgrades. Each simulation consisted of the following,

- Run 1: Minimum ANSI/AHRI 2007/LEED 2009 for Retail model
- Run 2: EEM 1 Multiplex Compressor Rack and Evaporator control with VFD
- Run 3: EEM 2 High Efficiency Display Cases plus EEM 1
- Run 4: EEM 3 Floating Head Pressure plus EEMs 1 and 2
- Run 5: EEM 4 Floating Suction Pressure plus EEMs 1, 2 and 3
- Run 6: EEM 5 Lighting Power Density (LPD), lighting Control and Daylight Harvesting plus EEMs 1, 2, 3 and 4.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Run 1	293,349	262,871	293,632	290,141	312,086	317,609	338,341	339,256	318,924	314,476	292,872	296,291
Run 2	292,153	261,793	292,361	288,838	310,571	315,830	336,328	337,171	317,222	312,997	291,603	295,095
Run 3	289,835	260,095	290,135	286,496	309,055	314,287	334,398	334,994	315,515	311,537	289,972	292,285
Run 4	268,759	241,185	268,915	265,938	287,783	295,563	315,658	316,726	295,147	289,883	268,904	271,102
Run 5	265,744	238,505	265,874	262,995	284,654	292,354	312,362	313,437	292,120	286,892	266,111	268,207
Run 6	222,081	197,126	222,478	221,171	238,573	246,531	265,503	266,985	247,465	240,734	223,430	226,048

Figure 2. Comparison of electric energy use by month

When utilizing multiple compressors, controlling of suction pressure by varying the speed of refrigeration compressors provides many advantages, such as reducing or eliminating the pressure range over which compressors are turned off and restarted. Since the system operation is defined and specified by the manufacturer to supply a minimum pressure for specific machinery, a typical cascade control of multiple compressors uses a 10 psi differential between each compressor's set-points to avoid frequent starts. For example, if 100 psi is required on a three compressor system, compressors may set to turn on and off between 100-110, 110-120, and 120-130 psig with the last set being the primary compressor. However, this cascade control develops pressures far higher than a facility needed to operate the system that results in running an inefficient system. To maximize the efficiency of a variable load refrigeration system, EEM 1 added a VFD to one compressor in each suction group. This variable speed compressor is acted as a trim capacity by adjusting to fluctuating demand to maintain pressure 1-2 psi above the desired minimum pressure set-points. The remaining compressors operate at full load and stage to meet the demand needed beyond its trim capacity. This speed reduction and the reduction in the system pressure combine to deliver large energy savings as shown in Figure 1. In addition, the base-case constant speed evaporator fan was replaced with a VFD. EEM 2 consisted of high efficiency display cases, including upgraded the base-case T8 fluorescent lighting fixtures in the cases to light-emitting diode (LED) fixtures. Evaporator fan motors were upgraded to ECMs, which reduces fan motor energy consumption significantly, when compared to the base-case using shaded-pole motors. Since fan motor energy is dissipated as heat inside the case, reducing the motor energy consumption reduces the refrigeration load, and in turn reduces the energy consumption of the refrigeration system. EEM 3 reset the head pressures of both the LT and MT down to the desired set points of WBT, as shown in Table 3. EEM 4 comprised of the addition of floating head controls to both the MT and LT suction groups. This measure allows the suction temperature to increase during the periods of low loads and thereby allows increased compressor efficiency. EEM 5 reduced LPD from the base-case by 25% and also incorporated daylight harvesting controls system at the sales and back of the house areas. The daylighting controls system dims the electric lighting in response to interior daylight levels by automatically dimming and staging of lighting loads depending on their distance from the ambient light sources, such as skylights and windows. Daylight offers benefits over electric lighting in large grocery stores. It can not only save energy by reducing the need for electric lights, but also there is some evidence from a recent study stated that natural daylight can improve retail sales by up to 6% (U.S. EPA 2008).

Conclusions and Recommendations

Utility costs are one of the significant expenses for facilities that operate industrial refrigeration systems. To minimize energy costs, efficient industrial refrigeration systems can be developed through the proper design, the use of premium efficiency equipment, the installation of appropriate system controls, and regular system maintenance. Compressor wear and tear over the years is primarily caused by the number of starts, operational cycles and the output pressure. A refrigeration system control such as a VFD greatly reduces stress on the compressor. The compressor slows as demand drops off and therefore fewer cycles take place. As a result, output pressure is kept at a minimum set-point pressure rather than operating over bandwidth set-points. Hence, compressor control, head pressure control, condenser fan control, and condenser sizing all have significant and interrelated effects on the total power consumption of a refrigeration system that utilizes evaporative condensing for heat rejection.

The benefits of energy efficiency measures and design strategies used in the two profiled case studies offer significant energy savings without compromising productivity. The two case studies have demonstrated that these design strategies can be applied in the design of new and existing refrigeration systems. In addition, the two properties were located in two geographic areas with distinctly different weather and climate patterns. Las Vegas is the largest city in the Silver State of Nevada and is located in the Mojave Desert (hot and dry climate) that has an average of 310 sunny days per year. Hot summer temperatures can reach into the triple digits. The temperatures drop into 20 degrees Fahrenheit for the coldest of winter nights. On the other hand, Columbus, Ohio has a humid continental climate. Summer temperatures reach up to 90 degrees Fahrenheit with some slight humidity and winters are cold with plenty of snow in Northern area. Therefore, the strategies and control technologies of the two case studies can also be applied in various world climatic zones, as a means of achieving significant improvements in energy savings while maintaining a satisfactory plant operation and its productivity. This paper provides highlight design considerations with the latest information on energy efficiency technologies in industrial refrigeration systems. However, this design brief may also be applied to the agriculture, food processing, manufacturing, fabrication, medical, high-tech, and biotechnology refrigeration industries.

It is recommended that building owners, facility managers, architects, and consulting engineers consider using the energy efficiency measures and design strategies presented in this paper for future refrigeration system upgrade projects. In doing so, implementers must recognize that, like other aspects of dynamic facilities, industrial refrigeration systems are quite diverse.

The sequences of operation and control of compressors need to develop, adjust, and continuously improve its optimum operation. The regular system adjustment and maintenance to meet a facility's desired set points while achieving efficient operation require case-by-case evaluation. To achieve this goal, an energy consultant must be involved with the integrated design team to keep the energy goals in mind during the decision-making process.

An example of proper sequences of operation is presented in Figure 3, the results from Las Vegas case study. Monthly electric energy consumptions of baseline and proposed energy models are compared with the actual electric bills. The baseline and proposed energy models are presented in red and orange colors respectively. The green color illustrates the actual electric energy consumptions for the month of March 2014 to February 2015. As a result of the regular system adjustment and maintenance, the facility achieved overall averaged savings of 14.5% in addition to the projected energy savings from the proposed energy simulation model. These additional savings occurred during the winter and spring seasons where the system is operating at part load. Proper sequencing can save energy due to differences in the part-load characteristics of compressors and the sizes of compressors in use. The efficiency profiles and capacities of all the compressors in the system should be considered when determining optimal sequencing and loading strategies for the particular system load. It should be noted that the simulation models utilized an hourly weather data fromTMY3 in the analysis. The TMY3 has Cooling Degree Day (CDD) of 4,657 CDD Base 60. It has averaged dry bulb (Tdb) and wet bulb temperatures (Twb) of 67.60 and 48.49 degrees Fahrenheit respectively. The averaged Tdb and Twb temperatures for the actual 2014 weather data are 73.55 and 50.29 degrees Fahrenheit respectively. On an average, TMY3 weather is hotter than the 2014 weather. This might be one of the reasons that the actual electric bills were lower than its estimated consumption from energy model. The two facilities qualified for substantial financial incentives from the local electric utilities as well as design assistance throughout the process.

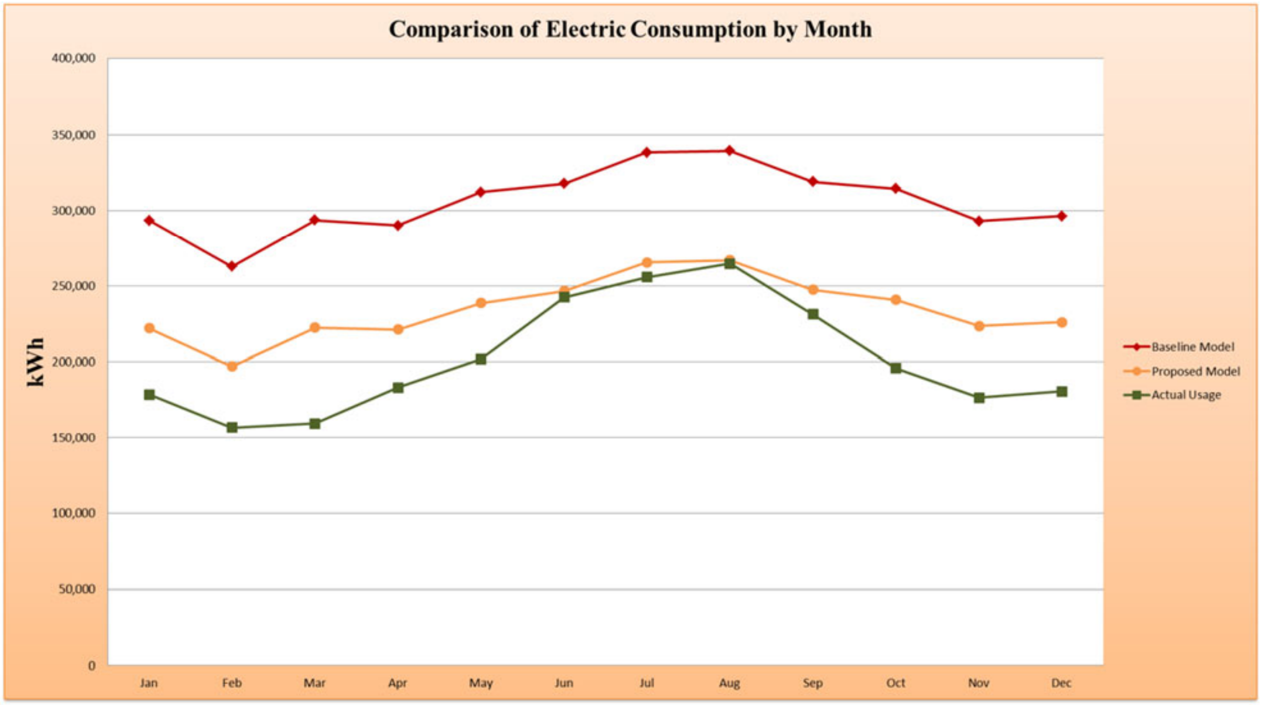


Figure 3. Comparison of electric energy use between simulation models and actual usage

Table 3. Comparison of baseline and proposed design model input parameters

Item	Attribute	Baseline	Proposed
		ANSI/AHRI 2007/LEED 2009 for Retail	Proposed Design
Compressor	Compressor Capacity Modulation	Multiplex Compressor System with Fixed Set Point	Multiplex Compressor System with Variable Speed Drive (VSD)
Evaporator	Evaporator Fan Speed Control	Constant Volume, Constant Operation	VSD Evaporator Fan
	Evaporator Design Approach Temperature	10°F	10°F
Condenser	Evaporative Condenser Fan Speed Control	Cycling One-speed Fan	VSD Speed Condenser Fan
	Evaporative Condenser Design Approach Temperature	18°F to 25°F Based on Design WBT	Mechanical Subcooling
		No Subcooling	Floating Head Low-Temperature (LT): 13°F WBT Following Approach
		No Floating Head	Floating Head Medium-Temperature (MT): 17°F WBT Following Approach
		No Floating Suction	Floating Suction LT/MT: 2 Degree Average Achieved Over the Year
	Evaporative Condenser Fan and Pump Power	330 Btu/Watt-hour at 100°F Saturated Condensing Temperature and 70°F WBT	As-Designed
Display Cases	Lights in Reach-in and Multideck Cases	Standard T8 Fluorescent Tube	LED Light Tube
	Fan Motor in Reach-in and Multideck Cases	Cycling One-speed Fan	ECM

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