Evaluation of the Axiom Exergy Refrigeration Battery™ System

Eric Kozubal, Adam Hirsch, and Ian Doebber

This work was done under agreement for Alliance Funded Technology Assistance, 15-00002.

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Technical Report
February 2015

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Introduction

Axiom Exergy contacted NREL to evaluate the Refrigeration Battery™[1] system models they produced using Microsoft Excel spreadsheets. The Refrigeration Battery system is intended to serve as a "thermal battery" to change the power profile of a grocery store that has a minimum of two refrigeration suction groups. In this system, a low temperature refrigeration rack (running at about -20°F suction temperature) would be used to solidify a phase change material (PCM) which is stored in insulated tanks at about 4°F. During periods when electrical energy and demand prices are high (on-peak hours), the medium temperature compressors and condensers shut down and the load on the corresponding refrigeration racks (running at about 18°F suction temperature) would be met by the PCM as it absorbs heat from the display cases and liquefies. The Refrigeration Battery can significantly reduce the central refrigeration system's energy use during the daytime (typically between 12:00 pm and 6:00 pm) when electricity is most expensive and shift this load to off-peak hours (night time) when electricity is less expensive.

Two spreadsheets and background slides were given to NREL for review. The first spreadsheet (Operational Calcs - V18 - 2015-02-03 - AR.xlsx), or "Operational Calculations", is used to evaluate the size and efficiency of the Refrigeration Battery system for a specific Bay Area supermarket. The second spreadsheet (Project Economics - V36 - 2014-02-03 - AR.xlsx), or "Project Economics", uses the outputs from the Operational Calculations along with 12 months of historical 15-minute power consumption data for the same store to determine the effects of the Refrigeration Battery on the store's power consumption profile (during both "charge" and "discharge" modes) and the net effect on the store's electricity bills.

Round-Trip Electrical Efficiency

The Refrigeration Battery system's round-trip efficiency (kWh_{out}/kWh_{in}) is primarily sensitive to the refrigeration system's temperature lift. The temperature "lift" of a refrigeration system is defined as the difference between the saturated suction temperature (which is slightly lower than the temperature of the display cases) and the saturated condensing temperature (which is slightly higher than the outdoor dry bulb air temperature). The energy efficiency ratio (EER) of a refrigeration system (in Btu/Wh) can be determined from the lift. At any given moment in time, the low temperature refrigeration system has a lower EER than the medium temperature system because the former has a higher lift. The saturated suction temperatures for each refrigeration system are fixed based on pre-defined display case set points. Conversely, the saturated condensing temperature varies as the dry bulb temperature of the outdoor air changes, causing the refrigeration system's lift to increase during the hot part of the day.

The Refrigeration Battery system "charges" (or solidifies) the PCM during cooler daytime and night hours when diurnal temperatures are low, lowering the temperature lift of the refrigeration systems. The Refrigeration Battery system "discharges" (or liquifies) the PCM during the afternoon when diurnal temperatures are high, thus offsetting periods of inefficient medium temperature refrigeration operation. By taking advantage of this diurnal shift (charging when the lift is lower and discharging when

[1] "Refrigeration Battery" is a trademark of Axiom Exergy Inc

the lift is higher), the round-trip electrical efficiency of the Refrigeration Battery is maximized. However, this method is unlikely to completely offset the impact of the 38°F difference in suction temperatures between low and medium temperature systems, thus limiting the efficiency to less than 100% in most cases.

In the process of determining inputs for refrigeration system energy modeling, NREL interviewed several refrigeration engineers from major manufacturers. System design and operational characteristics vary among stores; however, typical refrigeration systems are programmed to limit the minimum saturated condensing temperature to 70°F. Low temperature systems typically maintain saturated condensing temperatures that are 10°F above the dry-bulb temperature of the ambient air, while medium temperature systems typically maintain saturated condensing temperatures that are 15°F above the dry-bulb temperature of the ambient air (5°F higher than low temperature condensers). These programmed operational limits affect the refrigeration's efficiency and ability to fully leverage diurnal temperature swings where ambient temperature falls below the minimum saturated condensing temperature. Axiom Exergy's Operational Calculations document assumes that both the low temperature and medium temperature refrigeration systems maintain saturated condensing temperatures that are 5°F above the dry-bulb temperature of the ambient air (without a minimum set point).

System Size

The Refrigeration Battery system is sized to meet the peak load of the medium temperature refrigeration systems during the peak hours of the peak summer day based on 12 months of historical utility data. The peak load offset by the Refrigeration Battery (in Btuh) can be used to help determine the avoided power consumption of the compressors and condensers, or the power (kW) savings it produces. The average load offset can be used to help determine the avoided energy consumption of the compressors and condensers, or the energy (kWh) savings it produces.

Thermal load on the building will translate to additional thermal load (in Btuh) on the refrigeration systems. Understanding these load changes is required to properly design and size a thermal storage system. Figure 1 below shows a clear correlation between outdoor air temperature and the thermal load on the cases (labeled "Refrigeration Cooling Capacity" on the Y-axis) in a Colorado combination grocery-retail big box store.

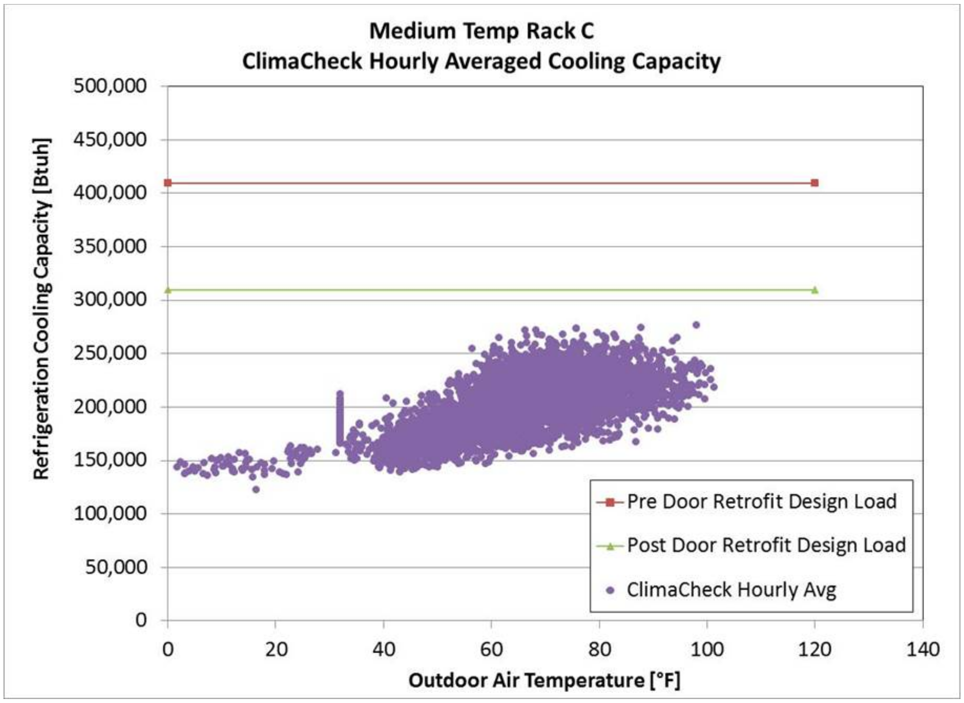

Figure 1

Economic Assumptions

Major factors in determining the economic benefits of the Refrigeration Battery system are purchase price, utility incentives, operation and maintenance costs (O&M costs), and utility time-of-use rate structures. Together, these factors are used to calculate simple payback (total purchase price / annual cost savings). The Project Economics calculations show a simple payback of about 2.9 years at a Bay Area supermarket. Correctly identifying all factors for each site is critical in determining payback accurately. Operational failure (for any type of energy storage system) is a risk factor that should be considered.

Evaluation

NREL was asked to evaluate the quality of the technical approach and assumptions going into the *Operational Calculations* and *Project Economics* models. This report discusses the findings of NREL's evaluation. The Operational Calculations spreadsheet calculates refrigeration thermal load by using historical runtime data collected from the site and converting this data to thermal load. A three-step process is used to determine thermal load during peak hours (when the Refrigeration Battery is in discharge mode):

1. Use the runtime data to calculate power draw using conversion factors from manufacturer data sheets (kW per nominal horsepower).
2. Use typical meteorological year (TMY3) data, which includes ambient dry-bulb temperatures, to determine a seasonally-averaged temperature lift imposed onto the refrigeration system during on-peak hours (in the afternoon).

3. Use compressor manufacturer's data sheets to convert temperature lift to EER. The EER, in conjunction with the power draw, is then used to determine thermal load (in Btu).

The above methodology was used because thermal power of the refrigeration system could not be directly measured or obtained from the store. Each step in the process introduces error in calculating thermal load. Step 1 relies on averaged performance of the compressors, and not real-time measured power draw. Step 2 relies on typical weather and not actual weather that correlates with the run-times that were taken from the store. Step 3 has some error because the temperature lift in each compressor is affected by the condensing temperature, which was assumed to be 5 °F higher than ambient temperature. These errors are not quantifiable given the scope of this project. However, the assumptions made in the three-step process are reasonable and conservative (as described next). The errors affect the calculation of thermal load, which then impacts the size of and total savings produced by the thermal energy storage system.

The Operational Calculations spreadsheet also uses the same three-step methodology to calculate thermal loads and refrigeration system power consumption when the Refrigeration Battery is in charge mode. Therefore, any bias error in calculating thermal load during the discharge mode is offset by the using the same thermal load calculation methodology for the charge mode. The Operational Calculations spreadsheet calculates a 73% round-trip electrical efficiency[2] of the Refrigeration Battery at this site. This calculation is not affected by the errors described above. Furthermore, the calculated efficiency is likely a conservative estimate due to the reasons listed below:

1. As stated earlier, medium temperature condensers typically operate at a saturated condensing temperature that is about 5°F higher temperatures than the saturated condensing temperature of low temperature condensers. The Operational Calculations spreadsheet assumes that the medium and low temperature systems use equal saturated condensing temperatures, meaning that the round-trip efficiency of the Refrigeration Battery is understated.
2. Axiom assumes a slower charge rate of the Refrigeration Battery system than what is possible. This forces the Refrigeration Battery to charge during hours when the ambient dry-bulb temperature is higher (increasing the lift during charging). If the charging period can be shortened, then the Refrigeration Battery system can further take advantage of diurnal temperature swings to improve round-trip efficiency.

We estimate that refrigeration efficiency could improve to 80% for stores with the revised condensing temperature approaches in item 1 above and improved operation of the Refrigeration Battery system from item 2.

The spreadsheet calculates the parasitic power consumption of various components of the Refrigeration Battery (primarily the liquid refrigerant and glycol pumps). It also calculates the power consumption of the refrigeration condenser fans during both charge and discharge modes. These calculations were found to be straightforward and adequate. Assumptions for pumping power efficiency were adjusted by Axiom based on feedback from NREL.

[2] $RoundTrip\ Efficiency = 100\% \times \left(\frac{Avoided\ compressor\ energy\ consumption\ during\ discharge\ (kWh_{out})}{Additional\ compressor\ energy\ consumption\ during\ charge\ (kWh_{in})}\right)$

The Operational Calculations spreadsheet also calculates the sizes of each main system component (PCM volume, PCM tank size, heat exchanger sizes, and pump sizes). The spreadsheet was adjusted to have appropriate over-sizing factors and heat losses, and the resulting sizing calculations were found to be adequate.

The Project Economics spreadsheet uses the outputs from the operational spreadsheet, site specific utility rates, and 12 months of historical 15-minute electrical demand data to calculate system cost, monthly peak demand savings (in kW), monthly energy savings (in kWh), monthly cost savings (in $/month) , and simple payback for the Bay Area supermarket. O&M costs were assumed to be rolled up in the purchase price of the system. These calculations were found to be straightforward and adequate. This spreadsheet does not consider the effects of errors in oversizing the Refrigeration Battery system. As a result, the simple payback calculation is not penalized due to incorrect system size. When specifying an actual system, more accurate sizing methods should be used.

Conclusions

As a result of our review, both spreadsheets were improved to more accurately calculate the Refrigeration Battery system's thermal load and economic payback. Both spreadsheets use sound methodologies given limited input information from the specific Bay Area supermarket being analyzed. The thermal load calculations likely introduce some error in determining the system size and energy savings, which will become important when specifying equipment. However, the outputs feed into the Project Economics spreadsheet with straightforward calculations for system payback. The economics spreadsheet assumes a correctly sized system, thus the payback is not affected by these sizing errors.

Axiom's Refrigeration Battery system is a promising technology that can provide thermal storage to shift expensive electricity use from peak hours during the day to less expensive hours during the night. The round-trip efficiency of the Refrigeration Battery is expected to be between 73% and 80%, which will likely improve as the Refrigeration Battery design is developed further. This efficiency is comparable to the round-trip efficiency of leading behind-the-meter electrochemical battery storage systems. As a result of its lower installed cost, the Refrigeration Battery system could provide an economical alternative to electrochemical battery storage systems. The system's simple payback was calculated to be 2.9 years, which should improve as the system design improves (Note: NREL did not review the cost estimates for the Refrigeration Battery system).

Future work should focus on directly measuring or better estimating thermal loads on the refrigeration systems. The following are suggested methods to improve thermal load predictions, which will minimize uncertainty in system sizing and help to further reduce risk to stakeholders:

1. Installation of a Climacheck (or similar) system to directly and accurately measure thermal loads on the refrigeration systems being analyzed.
2. Creation of a fundamental refrigeration model in an engineering-based software package (e.g. engineering equation solver, or EES) that could be used in conjunction with an 8760 hour simulation to calculate thermal loads and energy flows.

Axiom Exergy's Refrigeration Battery™ is a promising, efficient energy storage solution for supermarkets and refrigerated facilities. Their modeling efforts are based on sound engineering principals and economic assumptions.