# ENERGY SAVINGS OF PERMANENT MAGNET SYNCHRONOUS FAN MOTOR ASSEMBLY REFRIGERATED CASE EVAPORATORS

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**Prepared for:**

Chris Roman and Kate Zeng
San Diego Gas and Electric Company
8306 Century Park Court
San Diego, CA 92123


**Prepared by:**

M M Valmiki and Antonio Corradini, PE
Alternative Energy Systems Consulting, Inc.
www.aesc-inc.com


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For more information, contact ETinfo@sdge.com.



## Revision History

| Date | Revisions |
|---|---|
| March 2016 | Original release |
| May 2016 | Updates to energy usage and savings calculations, ROI |
| August 2016 | Laboratory fan curve testing and revisions based on updated market research |

# EXECUTIVE SUMMARY

In support of California's strategic plan to accelerate the penetration of energy efficiency technologies, AESC executed a study of a new fan motor technology with funding, guidance, and management by San Diego Gas & Electric Emerging Technologies Program. The primary goals for this project were to determine the energy savings and demand reduction of a permanent magnet synchronous motor with an innovative control design used in supermarket refrigerated cases.

A field trial comprising 9-12W fan retrofits was conducted at a San Diego supermarket. Baseline and retrofit data were collected for 35 and 33 days, respectively, without altering any other system conditions. A baseline of primarily electrically communicated motor driven fans was replaced with PMSM-driven fans. In-situ measurements included monitoring of fan circuit power, case air temperature and humidity, and spot measurements of individual fan assembly power before and after installation. Laboratory testing of airflow and fan curves was also performed for several of the removed baseline fans and the retrofit PMSM model.

The 173 fan assembly retrofits showed clear and consistent improvements in power factor, demand, and energy usage without negatively impacting case operation. The measurements were used to establish annual energy savings and demand reduction estimates. The host site realized a 37% demand reduction and energy savings of the end-use. The saved energy includes both reduction in fan energy consumption and the reduced refrigeration system energy necessary to reject the refrigeration load of the fan assemblies.

| Baseline Energy [kWh/yr] | Energy Savings [kWh/yr] | Baseline On-Peak FDemand [kW] | On-Peak Demand Reduction [kW] | Host Cost Savings [$/yr] | Baseline Power Factor | Retrofit Power Factor | Apparent Power Reduction [kVA] |
|---|---|---|---|---|---|---|---|
| 49,552 | 18,278 | 5.70 | 2.16 | $2,943 | 54% | 86% | 4.69 (60%) |

Fan savings were determined for medium-temp and low-temp cases and for ECM and shaded pole baselines. Market research showed that existing refrigerated cases are roughly 75% med-temp and 25% low-temp and use about 80% ECM fans and 20% shaded pole fans in California. Furthermore, it was found that the typical supermarket refrigeration systems have estimated COPs of 2.8 and 1.6 for med-temp and low-temp cases, respectively. Using field trial results for each of these case type and baseline fan situations along with weighting using the above factors, the usage and savings per fan retrofit were determined:

| Metric | Deemed Value |
|---|---|
| Baseline on-peak power [W] | 35.4 |
| Post on-peak power [W] | 20.1 |
| On-peak demand reduction [W] | 15.3 |
| Baseline energy [kWh/yr] | 308.8 |
| Post energy [kWh/yr] | 175.3 |
| Energy savings [kWh/yr] | 133.5 |
| Blended utility rate [$/kWh] | 0.161 |
| Full installed unit cost [$] | 103 |
| Simple payback [yr] | 4.8 |

With an idealized 100% market penetration of the 9-12W model, extrapolation to the California retail food segment suggests the statewide savings potential of this technology is about 262 GWh site energy and 30.1 MW demand reduction. The effectiveness, market potential, barriers to adoption, and ease of replacement suggest that this technology should be considered for immediate program inclusion.

# Abbreviations and Acronyms

| | |
|---|---|
| AESC | Alternative Energy Systems Consulting |
| AMCA | Air Movement and Control Association |
| DEER | Database for Energy Efficient Resources |
| ECM | Electrically Communicated Motors |
| EE | Energy efficiency |
| ET | Emerging technologies |
| EUL | Effective useful life |
| IPMVP | International performance measurement and verification protocol |
| M&V | Measurement and verification |
| PF | Power factor |
| PMSM | Permanent magnet synchronous motors |
| PSC | Permanent split capacitors |
| RH | Relative humidity |
| T/RH | Temperature and relative humidity |
| SDG&E | San Diego Gas and Electric |

# CONTENTS

# FIGURES

# TABLES

# INTRODUCTION AND BACKGROUND

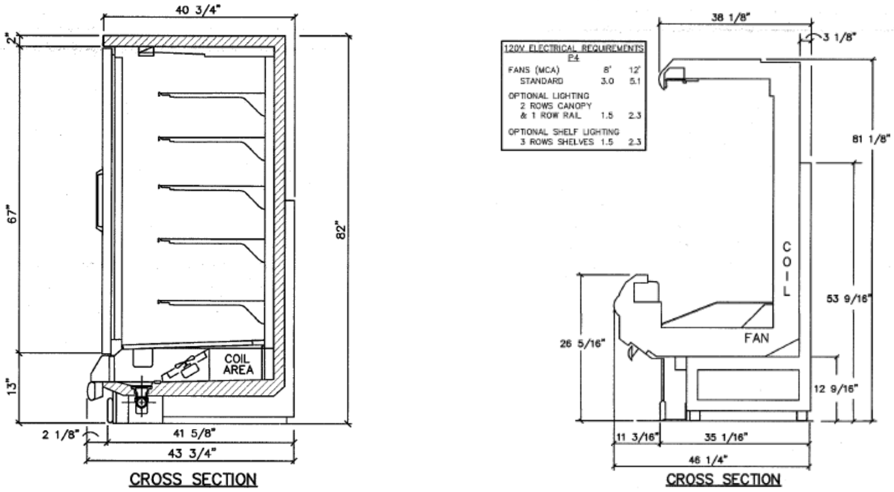
This study was performed by Alternative Energy Systems Consulting (AESC) on behalf of San Diego Gas and Electric's (SDG&E) Emerging Technologies (ET) program. The ET program strives to increase the exposure and success of emerging and underutilized energy efficiency and demand side management technologies in California. AESC is an energy engineering consulting company specializing in utility programs, technology assessments, demand side audits, and measurement and verification (M&V). This field test technology assessment was designed to provide information regarding a new motor design tailored for refrigerated case fan use.

Published literature on US commercial energy consumption estimates that about 30,000,000 GWh of site energy is consumed by motors in commercial refrigeration systems every year (Fricke & Becker, 2015) (NCI, 2013). This end-use presents a significant opportunity for energy footprint reduction using effective efficiency measures. The opportunity exists in one of the most energy intensive building types; California supermarkets and grocery stores have an average electrical energy use intensity of 44 kWh/ft$^2$-yr whereas the average commercial building is only 13 kWh/ft$^2$-yr (Lawrence Livermore Laboratory, 2016). Furthermore, California convenience stores which also typically have refrigerated case systems have an even higher average electric EUI of 51 kWh/ft$^2$-yr.

## TARGET MARKET AND SETTING

Refrigerated cases in retail food businesses come in a variety of designs with combinations of the following features: open front, closed glass door front, rear walk-in or door access, single or multideck, various air distribution paths, defrosting, antisweat heaters, lighting options and others (ASHRAE, 2014). In addition, each case will have specified evaporator coils and associated fan boxes. Each fan is typically powered by a small, fractional horsepower motor which rotates the fan blades, moving air across evaporator coils. For the purposes of this report, fan will refer to the assembly consisting of the fan blades and driving motor. The continuous air movement helps the refrigerated display case maintain a constant temperature throughout the case. Refrigerated cases are selected based on the store's refrigeration system design, refrigeration loads, and other required features. These cases are often categorized by the type of product being displayed such as meat, dairy, produce, frozen, and beverages.

**FIGURE 1 - EXAMPLE REFRIGERATED CLOSED AND OPEN CASE SCHEMATICS (FROM HOST SITE)**




Based on audit and implementation findings from PG&E's EnergySmart Grocer program and according to the ASHRAE Refrigeration Handbook, food retail buildings have a mix of roughly 75% low-temp cases and 25% med-temp cases.

The refrigeration load of these display cases comprises defrost heating, antisweat heaters, lighting, infiltration, radiation, conduction from the exterior, and the heat output of the fans. One source states that the heat output of evaporator fans accounts for about 2-5% of the refrigeration load for open cases (ASHRAE, 2014) (Faramarzi, 1999).

The majority of refrigerated case evaporator fans in supermarkets and other target buildings use 9-12W motors. However, smaller cases and walk-ins can often have other size motors, such as 4-8W motors in smaller deli cases or 38-50W motors in walk-in coolers or freezers. At the time of this study, the only available model was a 9-12W size. Thus, the study primarily focuses on this size fan and its respective market potential. However, other sizes are expected to be available in the near term and are discussed for future consideration.

Based on the available literature, there are approximately 27,693 buildings in the California consumer segment consisting of supermarkets, grocery stores, convenience stores, specialty food stores, liquor stores, and drug stores (US Census Bureau, 2013). Table 1 lists the breakdown of this customer segment as well as the number of installed evaporator fans estimated by using factors from a recent report on refrigerated case fan retrofits (Fricke & Becker, 2015) and industry input. The total estimated California 9-12W fan base is about 1,970,000 fans. This 9-12W fan base is the main population under consideration in this report since the fan retrofit only targeted this fan size. However, the manufacturer expects other model sizes to be available shortly and should incur similar savings effects found in this effort. Considering the three sizes listed in Table 1 would expand the fan base to about 3,400,000 units in California with an average equivalent fan size of about 16W. Supermarkets and grocery stores account for over 80% of the total baseline evaporator fan energy consumption and demand within these customer types.

**TABLE 1 - CALIFORNIA MARKET SIZE**

| FACILITY TYPE | NAICS CODE | # OF CALIFORNIA ESTABLISHMENTS | 4-8W MOTORS PER SITE | 9-12W MOTORS PER SITE | 38-50W MOTORS PER SITE |
|---|---|---|---|---|---|
| Supermarkets and other grocery stores | 44511 | 8,805 | 80 | 216 | 63 |

| | | | | | |
|---|---|---|---|---|---|
| Convenience stores | 44512 | 2,373 | 4 | 7 | 9 |
| Specialty food stores | 4452 | 2,896 | 20 | 50 | 16 |
| Liquor stores | 4453 | 3,815 | 0 | 2 | 15 |
| Drug stores | 44611 | 4,435 | 0 | 8 | 0 |
| Gas stations w/ convenience stores | 44711 | 6,089 | 8 | 2 | 6 |

Operation and maintenance of refrigerated cases is often conducted by a contracted service provider not associated with the design of the refrigeration system. Maintenance call-outs are typically ordered when a system component fails and evaporator fan fault detection diagnostics are uncommon. As a result, evaporator fans often run with increasingly degraded performance resulting in higher energy costs over time. Unfortunately, there is little cost-effective opportunity for savings through continuous monitoring of the fans since evaporator fans are small and almost entirely single speed. Thus, they are typically only repaired or replaced upon failure.

Although electrically commutated motors are mandated code for fans in walk-in freezers and refrigerated warehouses, there are no existing California codes for supermarket refrigerator case evaporator fans. Evaporator fan motors are a combination of ECMs, shaded pole, and permanent split capacitor motors. Regardless of the fan technology, it is unusual to find control systems that turn off the evaporator fans during periods of compressor inactivity. Instead, fans run continuously to move air throughout the conditioned space (Karas, 2006). As such, fans are usually operated year-round with the exception of necessary maintenance shutdowns and defrost periods for freezers. DEER 2014 estimates the effective useful life (EUL) of replacement fan motors is 15 years. Thus, any efficiency improvements will result in nearly 24/7 benefits over 15 years of useful life. However, it is possible that the 24/7 operation may result in a lower EUL than predicted in the DEER category.

# Incumbent Technology

Historically, a type of asynchronous induction motor called shaded pole has been used for refrigerated case fans due to their low cost and simplicity. However, these advantages are overshadowed by poor motor efficiency. The asynchronous shunting that allows the motor to start and stop significantly impacts performance, resulting in motor efficiencies of about 20%. This low efficiency means significant energy is wasted, which increases the thermal load in the refrigerated case making the refrigeration compressors run longer and more often in order to maintain the desired set point. While shaded-pole motors are still commonly found in refrigerated display cases across the state, more efficient motor technologies are eroding the shaded-pole motor market dominance (Fricke & Becker, 2015).

Permanent split capacitor (PSC) motors are a more efficient but less common fan motor technology. This motor type is able to realize efficiency improvements over shaded pole motors due to the addition of a small start-up winding. Once the motor reaches steady-state, the smaller winding becomes auxiliary, thereby approximating two-phase operation. Because of this design, PSC motors are able to achieve a motor efficiency of about 29% (NCI and PNNL, 2011).

Currently, the typical high-efficiency option is to employ electrically commutated motors (ECMs) in refrigerated display cases. This motor technology first rectifies the supplied AC current to DC current. The DC current is then commutated, or switched, by digital signals from simple rotor position sensors to an individually wound stator. This creates a magnetic field that rotates in sync with the motor. ECMs also make use of permanent magnets which eliminate the need for magnetizing current and decreases the overall energy use. Due to these design improvements newer ECMs are able to achieve efficiencies of up to 66% (NCI and PNNL, 2011). At the site used in this study, 92% of the baseline fans were driven by ECMs although this is much higher than is expected for the market, in general.

**FIGURE 2 – INCUMBENT BASELINE FANS AT THE HOST SITE**

One previous study suggested that supermarket evaporator fan motor populations consist of about 65% shaded pole and 35% ECM based on discussion with industry partners (Fricke & Becker, 2015). However, the percentage of ECMs in California food retail buildings is likely higher than the national average. The observed baseline in the test site was 92% ECMs. However, the store was specifically chosen because it had a high percentage of ECMs. Based on informal interviews with California refrigeration service providers, the baseline technology blend is about 80% ECM and 20% SP. This is the blend that is used as a recommendation for the final deemed value for program implementation. Savings are presented for each baseline motor type and further study or program findings could better determine industry standard practice and help clarify appropriate program baselines.

# EMERGING TECHNOLOGY

The motor technology examined in this study is an evaporator fan that uses a permanent magnet, synchronous AC motor (PMSM) with a new control design. These motors are inherently more energy efficient than all of the previously discussed motor technologies due to a number of design improvements.

First, energy savings are realized through the use of permanent magnets which reduce the power necessary to operate the motor. Similar to ECMs, the use of permanent magnets eliminates the need for magnetizing current and shaft brush. However, unlike an ECM this new synchronous motor runs off existing AC current without the need to rectify the current to DC. The elimination of the rectifying electronics realizes further energy efficiency improvement. The elimination of the electronics also decreases the motor complexity while increasing the reliability and service life of the motor (Fricke & Becker, 2015). Implementation of these PMSM fans has been shown to increase fan efficiency to 73%, thereby reducing both the direct energy use of the fans and the thermal load on the refrigeration system.

**FIGURE 3 - RETROFIT PMSM FANS AT THE HOST SITE**

Although the market penetration for this type of technology has been limited, recent advances in PMSM controller design has made the technology a more cost effective option for refrigerated case fan retrofit and new construction projects. The best next step would be to prove the technology's benefits through experimental testing and by improving cost competitiveness through utility incentives and increases in production efficiency. The cost of the new PMSM fans is equivalent to the same size ECM fans, according to the manufacturer. Based on a previous industry report, the typical ECM hardware cost is about $63 (Navigant, 2009). Thus the PMSM technology for a replacement 9-12W fan assembly is roughly $63, excluding labor. At the date of publishing, there was only one manufacturer offering this type of PMSM supermarket fan motor. Although only a 12W model was used in the study, the technology is scalable to smaller and larger size applications.

# ASSESSMENT OBJECTIVES

The goal of this technology assessment is to identify the demand reduction, energy savings, and operational benefits of a new PMSM fan design in supermarket refrigerated cases. To this end several objectives were established:

- Evaluate existing refrigerated case fan demand, energy usage, and power factor to establish a baseline case.
- Upgrade to PMSM fan and motor assemblies.
- Verify energy savings resulting from the technology during a post-installation period.
- Generate an assessment report for the completed project that can be used as a case study for future upgrade opportunities and utility incentive program design.

In order to accomplish these objectives, AESC designed a measurement and verification (M&V) plan adhering to IPMVP principles. The M&V plan is outlined in the following section and was designed to directly measure energy effects and the relevant factors and performance characteristics.

# MEASUREMENT AND VERIFICATION PLAN

The M&V plan for the technology assessment of the refrigerated case evaporator PMSM fans was based on a retrofit field test at a single San Diego area supermarket. The monitoring was done using calibrated metering equipment owned by AESC and California IOUs. Additionally, spot measurements were taken using verified instrumentation owned by the manufacturer. All sustained data logging instrumentation was installed by AESC engineers. Spot measurements were taken by the manufacturer during installation with oversight and recording by AESC engineers. The instrumentation, measurement plan, and analysis methods were agreed upon by AESC, SDG&E, the manufacturer, and host site. Additional follow-up laboratory testing of each fan type was also performed to complement the field trial.

The M&V plan followed a hybrid approach of options A and B of the IPMVP (key parameter measurement and all parameter measurement). The energy consumption of the fans was measured directly, a sample of case air conditions and airflow were measured directly, and the refrigeration load reduction was derived from direct measurements and refrigeration system specifications.

The measurement period spanned over two months between September 21 and November 30, 2015. This measurement period was selected to capture any variation in store operations or weather effects that may have existed. The baseline period lasted 35 days while the post-installation period lasted 33 days with several days in between for product installation.

## HOST SITE

The host site was a 42,930 square-foot supermarket built in 2004 located in San Diego, California in SDG&E territory. The hours of business operation are 6AM-12AM every day of the week, although staff performs restocking and maintenance outside of that timeframe. The building is located in California climate zone 7. The building is occupied 24/7 and the refrigerated cases operate 24/7 with freezers undergoing one brief defrost cycle each day.

Figure 4 and Figure 5 show several of the refrigerated cases at the host site.

FIGURE 4 - DELI CASES AND FROZEN FOODS CASES

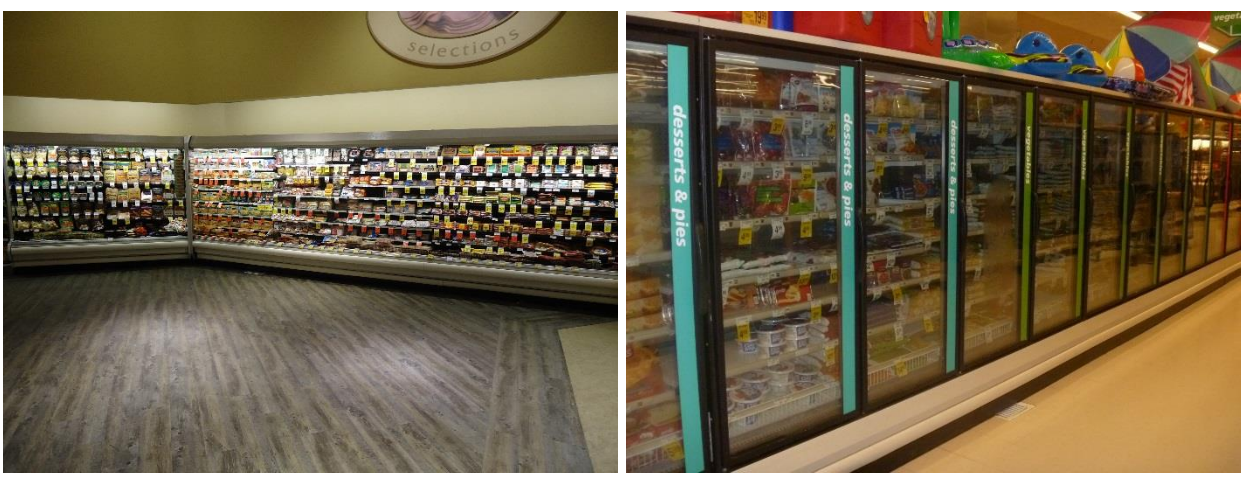


**FIGURE 5 - PRODUCE CASES AND DAIRY CASES**

Refrigeration is provided by a central system with the components and specifications listed in Table 2.

**TABLE 2 - CENTRAL REFRIGERATION SYSTEM**

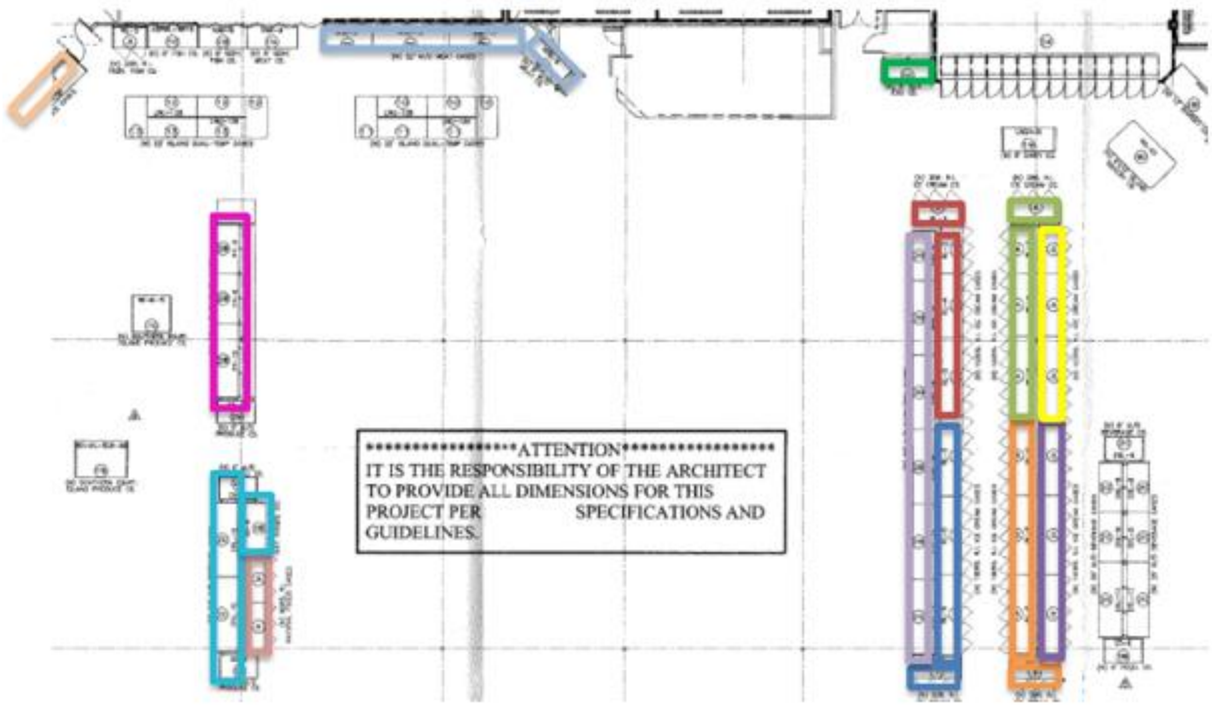
| REFRIGERATION SYSTEM COMPONENT | DESCRIPTION |
|---|---|
| Number of compressors | 13 (2 racks) |
| Design point kW/ton | 1.0 |
| Compressor | Copeland reciprocating |
| Condenser | SPX JC-180 evaporative |

The retrofitted fan circuits and associated quantity of fans are listed in Table 3. Of these fans, 13 used shaded pole motors while the remainder used ECMs. All fans targeted for retrofit used 9-12W motors and 92% of the baseline motors were ECMs. Each refrigeration circuit is color-coded to the store layout in Figure 6. The remaining cases were not retrofitted due to the nature of the case contents, for timeline expediency, and to limit project costs. A whole-store retrofit or future operations and maintenance (O&M) efforts could certainly target these additional units. In addition to the 173 fans that were replaced, there were an estimated (45) 9-12W fans, (100) 4-8W fans, and (76) 38-50W fans.

**TABLE 3 - FAN POPULATION AND CIRCUITS**

| Case contents | Circuit ID | Number of fans | Type |
|---|---|---|---|
| Frozen food | 1 | 18 | Closed |
| Frozen food | 2 | 15 | Closed |
| Frozen food | 3 | 18 | Closed |
| Frozen food | 4 | 15 | Closed |
| Frozen food | 5 | 15 | Closed |
| Frozen food | 6 | 12 | Closed |
| Natural foods | 9 | 6 | Closed |
| Meat | 20A | 20 | Open |
| Juice | 20B | 7 | Open |
| Eggs | 21A | 2 | Open |
| Dairy/deli | 21B | 17 | Open |
| Produce | 23A/B | 16 | Open |
| Produce/dairy/deli | 23C/D | 12 | Open |
| Total | | 173 | |

**FIGURE 6 - STORE LAYOUT WITH TARGETED CASES**




# INSTRUMENTATION

Power monitoring over the entire study period was performed using Dent ElitePro energy meters installed at the distribution panels which supply power to each fan circuit. Additionally, Onset HOBO T/RH data loggers were placed in a sample of the cases throughout the store to measure the case bulk air conditions (N=20 cases). Inside and outside air T/RH were also measured. The instrumentation is listed in Table 4. Note that the freezer temperature measurements were outside of the suggested operating range and accuracy specifications of the T/RH loggers. However, since the purpose of the T/RH logging was to compare bulk case air temperature before and after retrofit to ensure that case conditions were not affected, consistency was more important than accuracy for this monitored variable.

**TABLE 4 - MONITORING INSTRUMENTATION**

| MEASUREMENT | INSTRUMENT | ACCURACY | LOGGING INTERVAL |
|---|---|---|---|
| kW, kVA, A, V, pf | Dent ElitePro | <1% | 1 minute |
| T/RH | HOBO U12 | ±0.63°F, ±2.5% RH | 15 minutes |
| T/RH | HOBO UX100-011 | ±0.38°F, ±2.5% RH | 15 minutes |

**FIGURE 7 - CASE AIR T/RH AND ENERGY LOGGERS AT FAN CIRCUIT PANELS**


Additionally, spot measurements were taken at the baseline and retrofit fans during the installation. These included fan power measurements of every baseline and retrofit fan. The instrumentation for the spot measurements is listed in Table 5.

**TABLE 5 - SPOT MEASUREMENT INSTRUMENTATION**

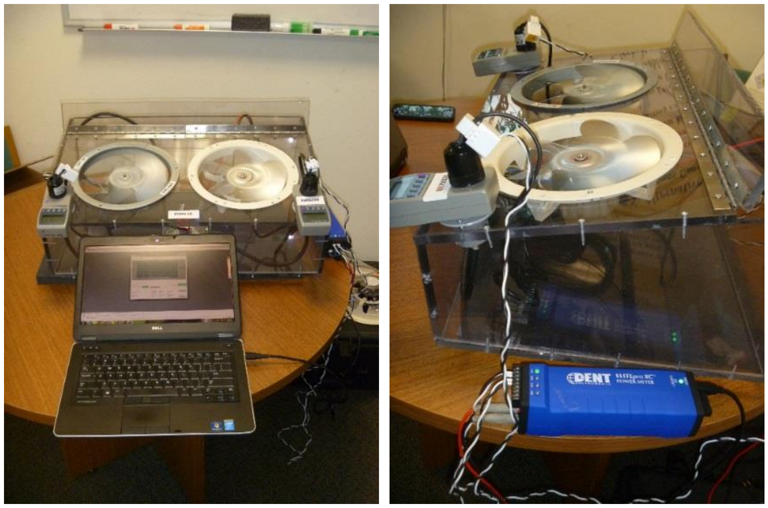
| MEASUREMENT | INSTRUMENT | ACCURACY |
|---|---|---|
| kW, kVA, A, V, pf | Kill A Watt | <1% |

**Error! Reference source not found.**Previous testing and field trials have shown that measuring the true power of both baseline and retrofit motors can be difficult due to the distribution of power across many harmonics beyond the base frequency. In order to validate the instrumentation selection, both AESC and the manufacturer conducted laboratory testing of the selected instrumentation. The manufacturer tested the power measurement instrumentation listed in Table 4 and Table 5 next to a calibrated Magtrol 4612B power analyzer and a custom system using a Veris E50 meter constructed by Oak Ridge National Lab. The meters were set up in a model fan circuit with the same measurement point locations for each meter. The manufacturer's testing showed that the measurements across all the instrumentation were consistent in order to verify the appropriateness of the instrumentation selection.

AESC also performed a similar office test of the two meters used in the field (P3 Kill A Watt and Dent ElitePro). Again, the measurements from the two complementary meters corroborated each other in order to serve as verification of the instrumentation selection. The results of this in-office testing are shown in Appendix A.

Figure 8 shows the AESC office test setup using a custom box provided by the manufacturer.

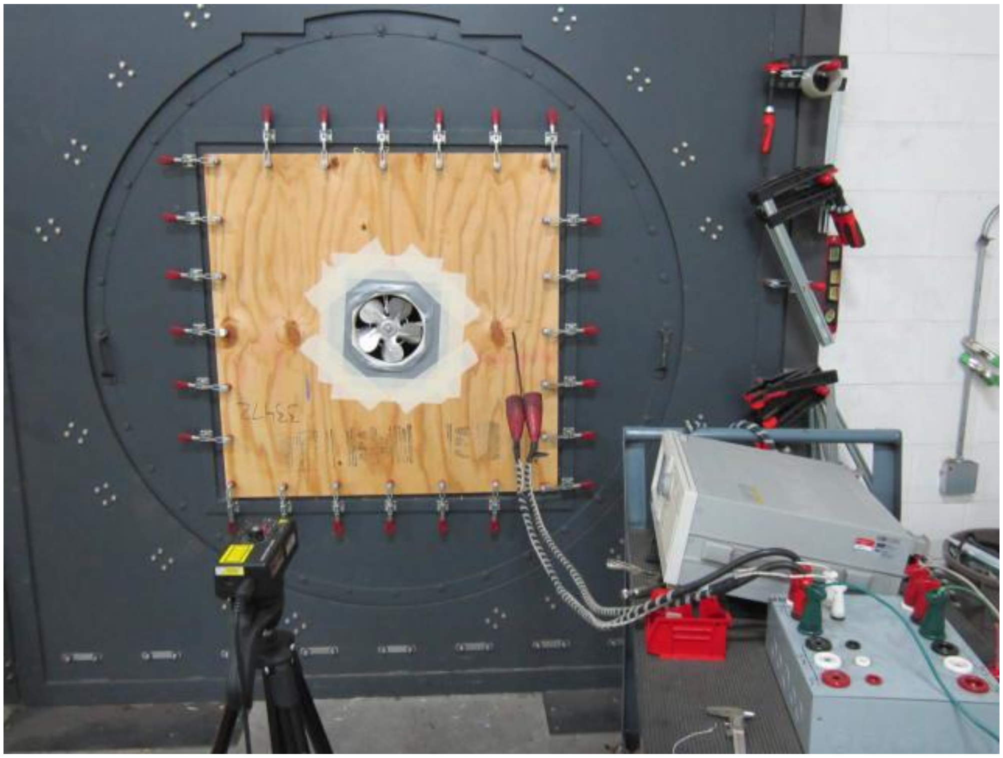
**FIGURE 8 - IN OFFICE TESTING OF FIELD INSTRUMENTATION**




## AMCA LABORATORY TESTING

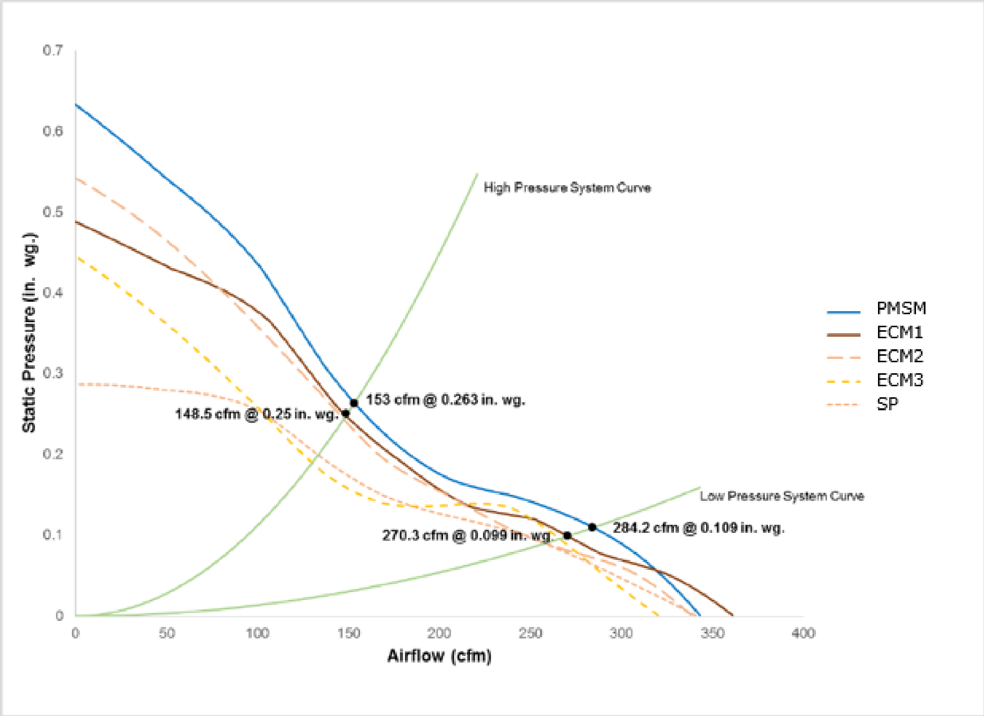
In addition to the field test, follow up testing performed at an Air Movement and Control Association laboratory (AMCA) under standardized testing conditions showed similar savings and that airflow was not decreased due to retrofit (Sheard & Smith, 2016). This is particularly important in order to verify that savings are not a result of decreased airflow rather than improved efficiency.

**FIGURE 9 – AMCA STANDARDIZED LAB TESTING SETUP**



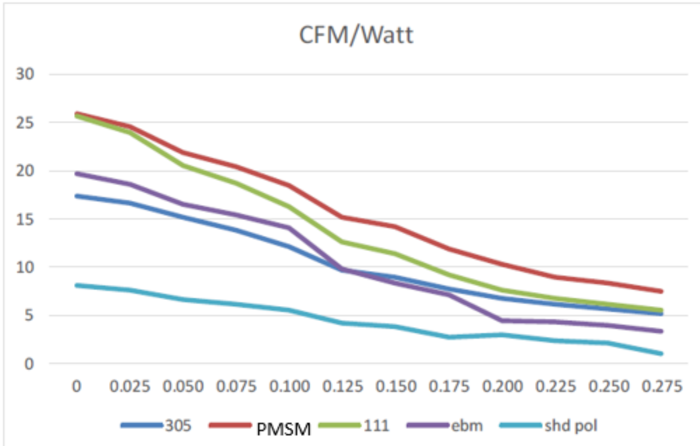
In Figure 10 the blue PMSM curve to the right of the others indicates airflow is not decreased by retrofit and savings can thus be attributed to improved fan and motor efficiency.

**FIGURE 10 – FAN CURVE RESULTS FROM AMCA TESTING OF RELEVANT FAN ASSEMBLIES (TEST STANDARD 210:07)**



The lab test results validated the power measurements of the fans in the field trial and showed that the retrofit fans produce at least as much airflow with less input power[1]. The lab testing used three baseline fans from the host site and the same replacement PMSM model. Figure 11 shows the fan curves for the PMSM model and baseline motor types.

**FIGURE 11 – AMCA LAB TESTING FAN INPUT POWER PER CFM (Y-AXIS) FOR VARYING SYSTEM PRESSURE (X-AXIS)**




# ANALYSIS METHODS

The data were treated to account for defrost events and to correct for some unexpected loads on the measured circuits. The freezer cases are programmed to defrost once a day for 30 minutes at various times during the night. During the defrost events, the fans are turned off and electric heaters are turned on. The measured data revealed that electric defrost heaters were unexpectedly on the measured fan circuits. In order to correct for this, the heater power spikes were removed from the data and energy consumption was adjusted by excluding this time period from kWh calculations.

Additionally, there were other unexpected loads on the fan circuits that were measured at the distribution panel. Although the best information available suggested that the circuits were dedicated solely to the fan motors, there were additional connected loads including lighting, and perhaps other unknown constant loads. However, since the connected loads were either periodic (e.g. defrost heaters) or constant (e.g. lighting), the data was easily corrected to represent only the fan loads. Figure 12 shows the correction of these unexpected loads in an example freezer case.

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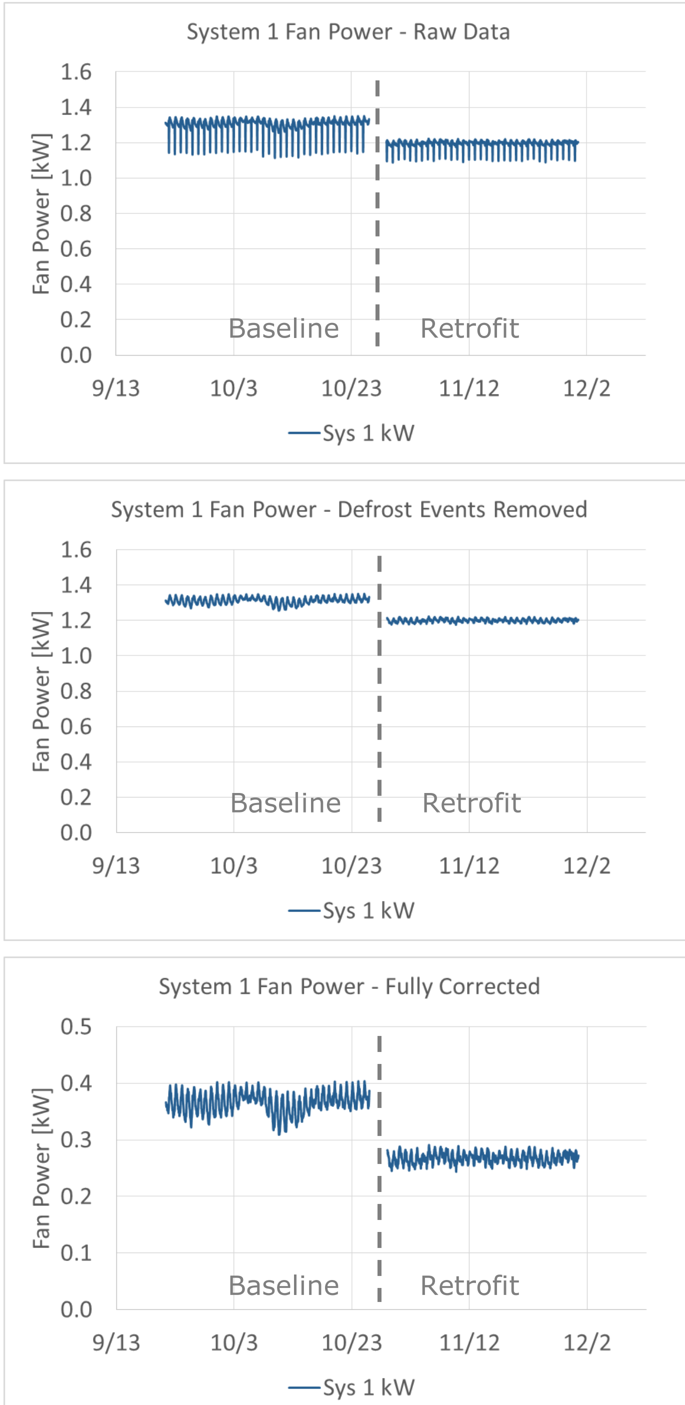
[1] These lab test findings are in contrast with previously reported spot measurements taken at the host site. These spot measurements were later proven to be inaccurate and the AMCA lab testing is included in the report in lieu of these earlier measurements.

**FIGURE 12 - EXAMPLE OF RAW FAN CIRCUIT DATA, WITH DEFROST CYCLES REMOVED, AND CONSTANT NON-FAN LOADS REMOVED**

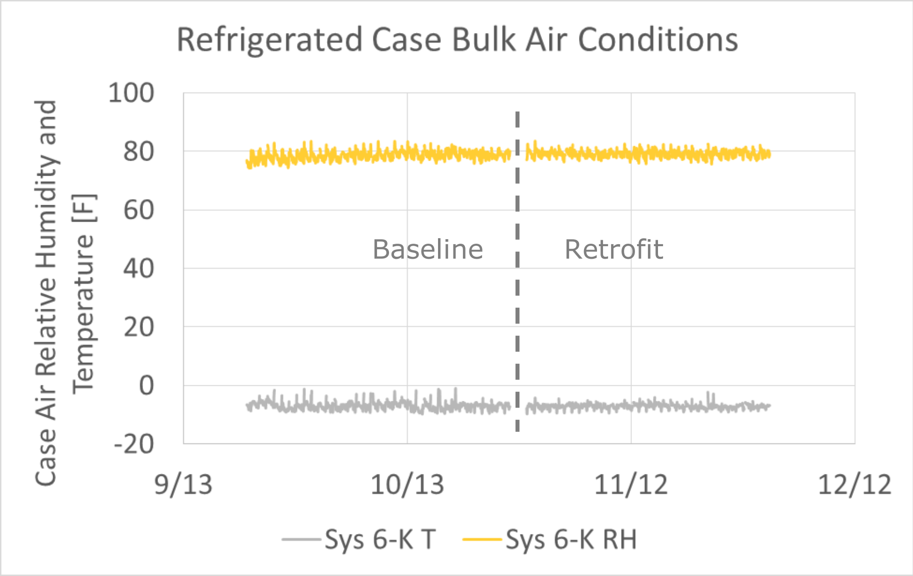



Using the spot measurements of each fan, the constant non-fan loads were established for each circuit based on comparison with the circuit-level measurements taken at the breakers with the Dent loggers. This correction was a constant reduction in all Dent circuit-level measurements at each timestamp. On average, the absolute reduction was 0.35 kW (44%) with minimum and maximum absolute corrections of -0.05 kW and 0.94 kW. This method is justified by the validated spot measurements, the constant nature of the Dent measurements, the circuit level power factor measurements suggesting lighting and heater loads, and the load pattern of the corrected data that is representative of typical supermarket fan operation.

# RESULTS

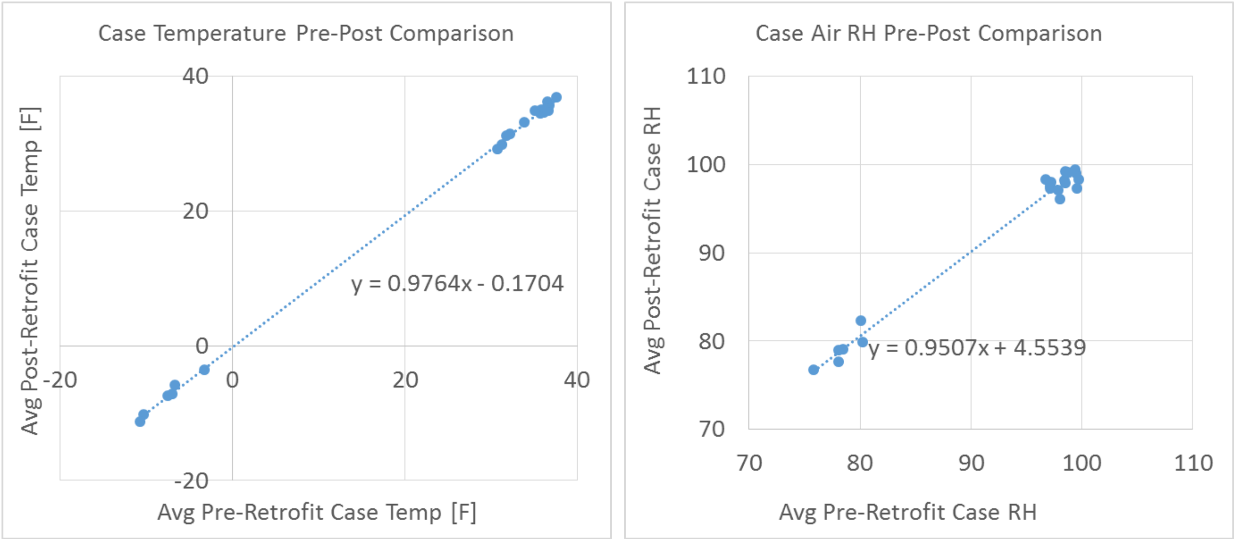
In order to ensure that energy savings were not being achieved at the expense of case performance and product safety, T/RH measurements were recorded at a sample of the cases. The collected data showed temperature and humidity levels remained consistent between the baseline and post-installation periods, indicating that the bulk air setpoints were not negatively impacted. Figure 13 shows an example of consistent T/RH before and after retrofit.

FIGURE 13 - BASELINE AND POST-INSTALLATION T/RH MEASUREMENTS IN AN EXAMPLE FREEZER CASE



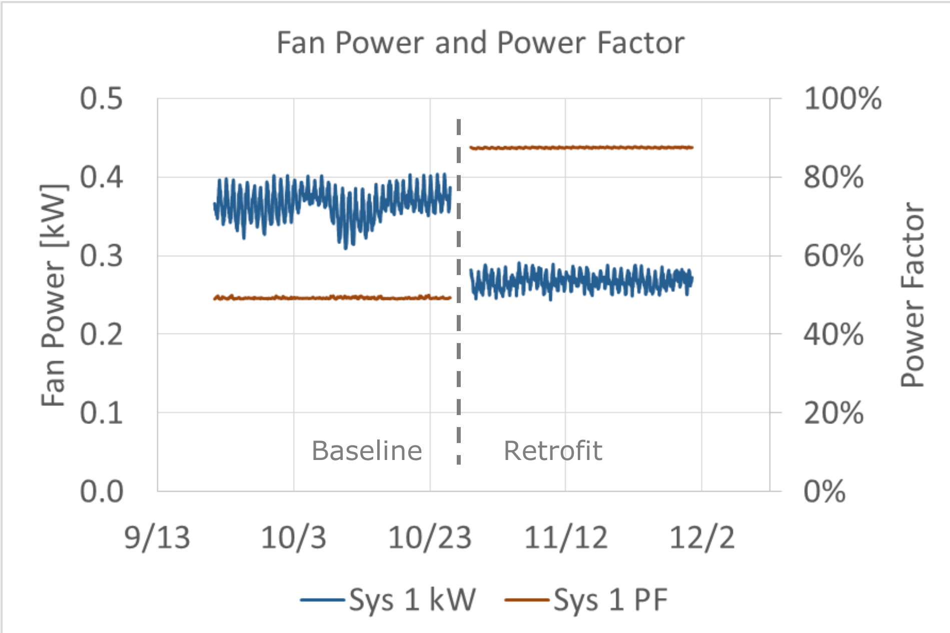

This consistency was seen across all instances as shown in Figure 14 which compares the average temperature and humidity for each case between the baseline and post-installation periods. A trend line with a slope close to one indicates consistent case conditions and performance before and after retrofit.

FIGURE 14 – AVERAGE TEMPERATURE AND HUMIDITY COMPARISONS FOR EACH CASE



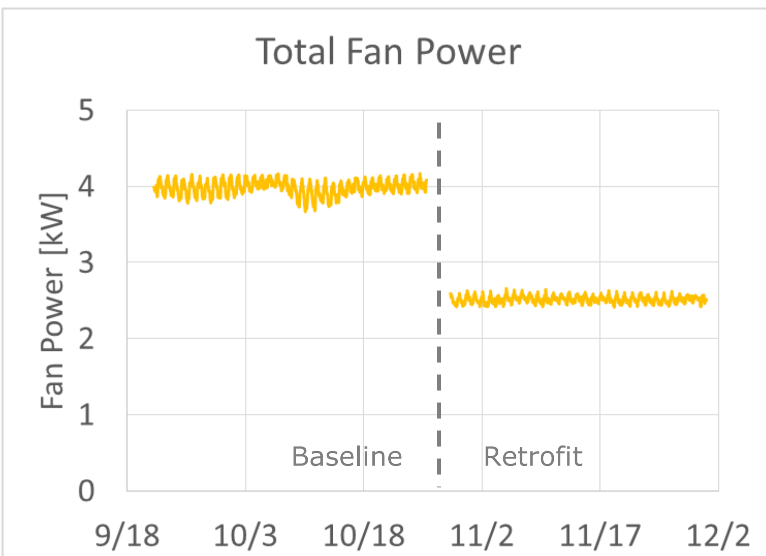
Once it was shown that there was no negative impact on the ability to maintain case air conditions, the energy efficiency improvements were quantified. Since the motors are fixed speed and operate 24/7 except for the brief defrost events, the demand reduction and power factor improvements were experienced instantaneously, without need for tuning or commissioning. Figure 15 shows this clear effect on the power of refrigeration circuit 1 which has 18 fans in closed freezer cases.

**FIGURE 15 - REFRIGERATION CIRCUIT 1 DEMAND AND POWER FACTOR FOR THE BASELINE AND POST-INSTALLATION PERIODS**




The same effect was seen for each fan, case, and circuit. Figure 16 shows the effect on demand for the total population of targeted fans.

**FIGURE 16 – DEMAND AND POWER FACTOR FOR ALL TARGETED CASES ACROSS THE BASELINE AND POST-INSTALLATION PERIODS**

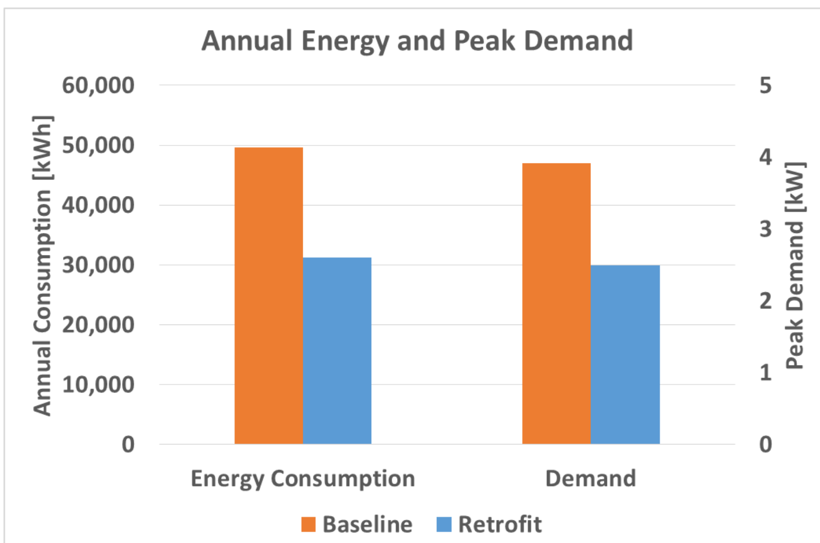


Using this measured data, the annualized energy savings, apparent demand reduction, and source current reduction were calculated for the total retrofitted fan population. Table 6 and Figure 17 show the calculated total savings and demand reduction for the host site realized from the project. Since only 173 of the estimated 218 fans with 9-12W motors at the host site were replaced, it is expected that the savings values would be about 26% greater if all 218 fans of this size were retrofitted. Additionally, forthcoming manufacturer models will also be able to address the smaller and larger fan sizes with motors of 4-8W or 38-50W. Replacing these other sizes could potentially contribute additional demand reduction and energy savings up to two times that achieved by the actual retrofit.

TABLE 6 - ANNUAL ENERGY SAVINGS AND DEMAND REDUCTION OF THE HOST SITE (173 FANS UNDER STUDY)

| BASELINE FAN USAGE [KWH] | BASELINE FAN LOAD REFRIGERATION USAGE [KWH] | TOTAL BASELINE USAGE [KWH] | FAN ENERGY SAVINGS [KWH] | FAN REFRIGERATION LOAD ENERGY SAVINGS [KWH] | TOTAL ENERGY SAVINGS [KWH] AND % |
|---|---|---|---|---|---|
| 34,514 | 15,038 | 49,552 | 12,731 | 5,547 | 18,278 (37%) |

FIGURE 17 – ENERGY AND DEMAND SAVINGS OF THE HOST SITE



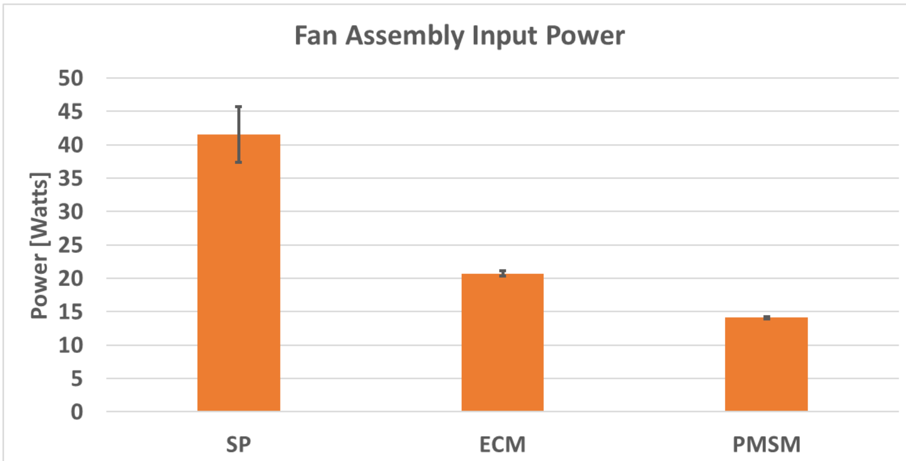

The annual energy savings due to reduced refrigeration load were calculated using the following equation.

$$\Delta E_{refrigeration} = \frac{\Delta kW_{avg} * T\ hrs * 3{,}412\ \frac{Btu}{kWh} * \beta\ kW/ton}{12{,}000\ \frac{Btu/_{hr}}{ton}}$$

In the case of freezers, $T$ is 8,578 hours in order to account for the daily 30 minute defrost cycles during which fans are not powered. For all other cases without defrost, $T$ is 8,760 hours since the fans operate all day long without interruption. $\beta$ is the overall, average efficiency of the refrigeration system which was taken to be 1.3 kW/ton for the med-temperature cases and 2.2 kW/ton for the low-temperature freezer cases. These refrigeration efficiency parameters were based on a literature survey of typical supermarket refrigeration system efficiencies (Fazamari, 2004) (Deru M. , 2011) (Little, 1996) (PG&E, 2016).

Since potential retrofit facilities will have varying numbers of fans, it is useful to quantify the savings for each retrofit unit. This will allow for savings estimations of projects of varying size and scope. Figure 18 shows the input power per fan type with 95% confidence interval demarcations. This power is for direct fan assembly input power only and does not include refrigeration system power.

FIGURE 18 – INPUT FAN ASSEMBLY POWER FOR EACH 9-12W UNIT TYPE (95% CONFIDENCE INTERVALS)




Using these empirical findings per fan type, the annual demand and energy savings for each baseline type and case type were determined as listed in Table 7.

TABLE 7 – PER FAN ASSEMBLY DIRECT SAVINGS (EXCLUDES REFRIGERATION INTERACTIVE EFFECTS)

| | Med-temp | | Low-temp | |
|---|---|---|---|---|
| | Shaded Pole Baseline | ECM Baseline | Shaded Pole Baseline | ECM Baseline |
| Baseline on-peak power [W] | 41.6 | 20.7 | 41.6 | 20.7 |
| Post on-peak power [W] | 14.1 | 14.1 | 14.1 | 14.1 |
| On-peak demand reduction [W] | 27.5 | 6.6 | 27.5 | 6.6 |
| Baseline energy [kWh/yr] | 364.3 | 181.5 | 356.7 | 177.7 |
| Post energy [kWh/yr] | 123.8 | 123.8 | 121.2 | 121.2 |
| Energy savings [kWh/yr] | 240.5 | 57.7 | 235.5 | 56.5 |

Using the simplified COP model of the refrigeration system as described above, the refrigeration components of demand and energy savings were calculated as listed in Table 8.

TABLE 8 – PER FAN ASSEMBLY REFRIGERATION SYSTEM SAVINGS

| | Med-temp | | Low-temp | |
|---|---|---|---|---|
| | Shaded Pole Baseline | ECM Baseline | Shaded Pole Baseline | ECM Baseline |
| Baseline on-peak power [W] | 14.9 | 7.4 | 26.0 | 13.0 |
| Post on-peak power [W] | 5.1 | 5.1 | 8.8 | 8.8 |
| On-peak demand reduction [W] | 9.8 | 2.3 | 17.2 | 4.2 |

| | | | | |
|---|---|---|---|---|
| Baseline energy [kWh/yr] | 130.1 | 64.8 | 222.9 | 111.1 |
| Post energy [kWh/yr] | 44.2 | 44.2 | 75.8 | 75.8 |
| Energy savings [kWh/yr] | 85.9 | 20.6 | 147.2 | 35.3 |

Finally, by using these results for each type of case and baseline motor along with the factors in Table 9, average deemed savings per unit retrofit can be established. These factors were determined for California using existing information from ASHRAE, the PG&E EnergySmart grocer program, and discussions with refrigeration service providers.

**TABLE 9 – WEIGHTING FACTORS FOR CALIFORNIA MARKET (ASHRAE, 2014)**

| WEIGHTING FACTOR | VALUE |
|---|---|
| Med-temp % | 75% |
| Low-temp % | 25% |
| Shaded pole baseline % | 20% |
| ECM baseline % | 80% |

Using these factors and the savings listed in Table 7 and Table 8, the following equation was used to establish an estimated average, deemed value for each potential fan assembly retrofit.

$$Deemed\ Savings = \omega_{med-temp}(\omega_{SP} * Energy\ Savings_{SP-med} + \omega_{ECM} * Energy\ Savings_{ECM-med}) + \omega_{low-temp}(\omega_{SP} * Energy\ Savings_{SP-low} + \omega_{ECM} * Energy\ Savings_{ECM-low})$$

Table 10 lists the weighted average annual usage, demand, and savings per fan as determined by this method.

**TABLE 10 – PER FAN WEIGHTED USAGE, DEMAND, AND SAVINGS (FAN INPUT POWER AND REFRIGERATION SYSTEM EFFECTS)**

| Metric | Deemed Value |
|---|---|
| Baseline on-peak power [W] | 35.4 |
| Post on-peak power [W] | 20.1 |
| On-peak demand reduction [W] | 15.3 |
| Baseline energy [kWh/yr] | 308.8 |
| Post energy [kWh/yr] | 175.3 |
| Energy savings [kWh/yr] | 133.5 |
| Blended utility rate [$/kWh] | 0.161 |
| Full installed unit cost[2] [$] | 103 |
| Simple payback [yr] | 4.8 |

These demand reduction and energy savings figures are presented only for the 12W model replacement of 9-12W baseline fans. However, it is reasonable to expect similar power factor improvement and energy savings with smaller and larger size models such as 4-8W or 38-50W fans.**Error! Reference source not found.**

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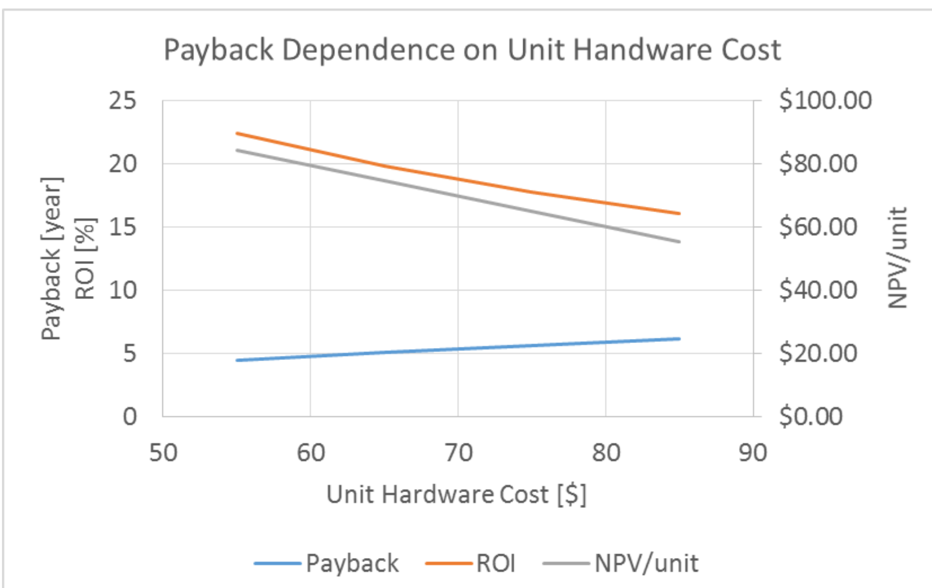
[2] Based on hardware cost of $63 and expected labor of 20 minutes at a rate of $120/hr.

# DISCUSSION AND RECOMMENDATIONS

The new PMSM fans were shown to improve energy efficiency effectively and consistently across all instances of retrofit. The tight confidence intervals suggest that the reported energy savings, demand reduction, and power factor improvement are well assured. The actual process of retrofit installation is rapid and easy if sized properly. The economics of the technology appear attractive for both early retirement retrofits and for replacement upon baseline motor burnout or with new case installations. Naturally, the return on investment will be better for new case installations and replacement on failure of incumbent fans, but the study suggests that early retirement projects should achieve payback within 5 years, well within the estimated useful life.

Based on best available information, the incremental cost per installed unit for an early retirement replacement without any utility incentives is about $103. This incremental cost range was based on 20 minutes of labor per unit at $120/hour and a fan assembly cost of $63 for the 9-12W model. This cost is based on parts and labor estimates from the manufacturer, literature survey of ECM costs, and a supermarket refrigeration service contractor. The manufacturer has stated that the new PMSM fan is estimated to have the same cost as a similar ECM model, with installed costs dependent on application, location, and project scale. Based on this and project results, the expected payback is estimated to be 4.6-5.4 years as shown in Figure 19 for an expected hardware cost range of $58 to $75. Assuming a 15 year EUL, this corresponds to a net present value (NPV) per fan of $181-$197 and a return-on-investment (ROI) of 19%-22%. Using these fans as replacements for failed units or in new construction will provide even better return due to less incremental cost.

**FIGURE 19 - PAYBACK, ROI, AND NPV DEPENDENCE ON FAN UNIT HARDWARE COST FOR 9-12W BASELINE FANS**




In order to quantify the total available California market potential, the results in Table 1 and Table 10 were combined. As a result, the total market potential for 9-12W fans is estimated to be 262 GWh/yr of site energy savings, as shown in Table 11. The $CO_2$ emissions factor, average commercial electricity rate, and source energy factor are taken from available literature (Deru M. a., 2007) (Energy Information Administration, 2015) (U.S. DOE). These results assume that the incumbent market motor population is similar to that of the host site in terms of the proportion of shaded pole and ECM motors. If there are substantially more shaded pole motors in the market than at the host site, savings potential could be significantly higher. Including forthcoming smaller and larger models for 4-8W and 38-50W fans could increase the estimated market potential by 2-3 times.

**TABLE 11 – CALIFORNIA MARKET POTENTIAL WITH 100% PENETRATION**

| SITE ENERGY SAVINGS [GWH/YR] | SOURCE ENERGY SAVINGS [GWH/YR] | DEMAND REDUCTION [MW] | $CO_2$ REDUCTION POTENTIAL [METRIC TONS/YR] |
|---|---|---|---|
| 262 | 790 | 30.1 | 92,195 |

# RECOMMENDATIONS

Given the consistent and assured energy savings, power factor improvement, and demand reduction achieved by the retrofit, the new PMSM technology should be considered for further utility support and potential inclusion into an incentive program. Given the similarity to other existing program measures and the high level of confidence in per unit savings, a deemed, rebate measure or direct install may be the most appropriate program paths. In the case of SDG&E, the product would be a good fit for the Energy Efficiency Business Rebates (EEBR) program, in particular within the Food Service and Refrigeration category.

The observed baseline was 92% ECM fans, although a previous study suggested the typical national baseline is about 65% shaded pole and 35% ECM based on "discussions with industry partners" (Fricke & Becker, 2015). Discussion with refrigeration service providers suggested that a mix of 80% ECM and 20% SP is typical in California. Further study into industry standard practice or customer surveying could help clarify representative baseline conditions.

The PMSM motor and control technology scaled to other size motors could greatly expand the market potential energy savings listed in Table 11. Since a program could easily scale the rebate value with the motor size, the smaller and larger models should be considered for program inclusion when available. If necessary, additional customer surveying of existing fan populations or laboratory testing of smaller and larger models could provide information for this potential scaled offering.

In addition to refrigerated cases, the motor technology may also be applied to fans in vending machines, walk-in freezers, condensers, and single speed HVAC fans. The installed base of these unstudied applications is extensive and could easily dwarf the supermarket case setting studied here. Across the U.S. there are approximately 3,567,000 installed motors in vending machines, alone (ASHRAE, 2014). Further market or M&V study of these other applications would be prudent in the hopes of additional program development beyond food retail refrigerated cases.

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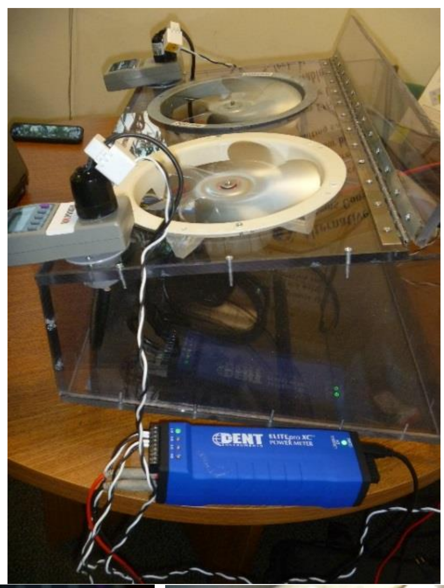
# APPENDICES

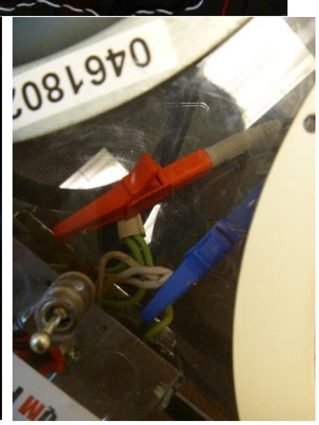
## APPENDIX A – INSTRUMENTATION VALIDATION

In office testing was performed to validate the accuracy of Dent and Kill A Watt metering; the test was not intended as fan performance testing. The following should serve as proof of accuracy of both metering systems. Dent meters are factory calibrated and Kill A Watt meters were used for their portability and spot measurements. For additional confidence, both instruments were also tested next to a calibrated power quality analyzer and custom Veris E50 system built by Oak Ridge National Labs at the manufacturer's laboratory. Dent power factor is calculated using kW and kVA measurements rather than the power factor output, as that only considers the first harmonic.

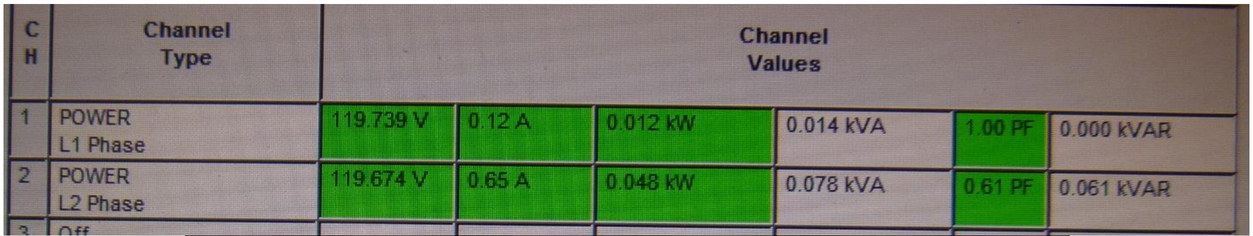
| | PMSM Motor 1 | | PMSM Motor 2 | | ECM Motor 1 | | ECM Motor 2 | |
|---|---|---|---|---|---|---|---|---|
| | Dent | Kill A Watt | Dent | Kill A Watt | Dent | Kill A Watt | Dent | Kill A Watt |
| V | 119.7 | 120.0 | 119.2 | 118.9 | 119.7 | 119.8 | 118.9 | 119.0 |
| A | 0.12 | 0.11 | 0.12 | 0.12 | 0.65 | 0.65 | 0.40 | 0.40 |
| VA | 14 | 15 | 15 | 15 | 78 | 78 | 47 | 48 |
| W | 12 | 13 | 13 | 13 | 48 | 49 | 26 | 25 |
| pf | 0.86 | 0.87 | 0.87 | 0.89 | 0.62 | 0.63 | 0.55 | 0.52 |





PMSM 1 and ECM 1 motors



| CH | Channel Type | Channel Values | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | POWER L1 Phase | 119.739 V | 0.12 A | 0.012 kW | 0.014 kVA | 1.00 PF | 0.000 kVAR |
| 2 | POWER L2 Phase | 119.674 V | 0.65 A | 0.048 kW | 0.078 kVA | 0.61 PF | 0.061 kVAR |
| 3 | Off | | | | | | |

| | PMSM 1 | ECM 1 |
|---|---|---|
| Power Factor |   |   |
| Watts |   |   |
| Amps |   |   |

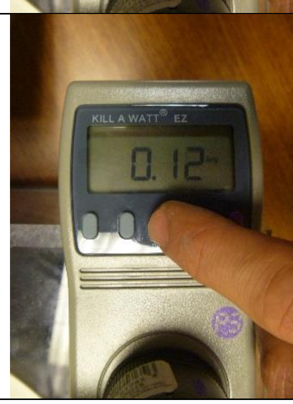
PMSM 1 and ECM 2 motors

| CH | Channel Type | Channel Values | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | POWER L1 Phase | 118.904 V | 0.12 A | 0.013 kW | 0.015 kVA | -0.99 PF | -0.002 kVAR |
| 2 | POWER L2 Phase | 118.904 V | 0.39 A | 0.025 kW | 0.046 kVA | -0.97 PF | -0.006 kVAR |

| | ECM 2 |
|---|---|
| Power Factor |  |
| Watts |  |
| Amps |  |

PMSM 1 and PMSM 2 motors

| CH | Channel Type | Channel Values | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | POWER L1 Phase | 119.225 V | 0.12 A | 0.013 kW | 0.015 kVA | -0.99 PF | -0.002 kVAR |
| 2 | POWER L2 Phase | 119.289 V | 0.12 A | 0.013 kW | 0.015 kVA | 1.00 PF | 0.000 kVAR |
| 3 | Off | | | | | | |

| | QSync 2 |
|---|---|
| Power Factor |  |
| Watts |  |
| Amps |  |

# APPENDIX B – PRE AND POST AVERAGE BULK AIR CONDITIONS FOR EACH SAMPLED CASE

In addition to the evidence presented in Figure 13 Figure 14, the following average T/RH data points for each sample case show that performance was not impacted by the retrofit. This supports that the energy consumption comparison is a fair comparison.