Analysis of energy savings and peak demand reduction from control measures for grocery stores

Weimin Wang[1], Yulong Xie[2], Nick Fernandez[2], Srinivas Katipamula[2]

[1]University of North Carolina at Charlotte, Charlotte NC 28223
[2]Pacific Northwest National Laboratory, Richland WA 99352

ABSTRACT

Grocery stores represent an energy-intensive building type that consumes about 5% of the total primary energy used by commercial buildings in the U.S. Many literature studies presented possible control strategies for grocery stores qualitatively or reported the measured savings from a specific case study. This paper presents a more systematic study to quantify the benefits of 15 energy efficiency (EE) measures and 4 demand response (DR) measures, most of which are applicable to many existing grocery stores. The baseline model is a hypothetical building with characteristics of grocery stores constructed in 1990s. Each EE measure was evaluated against the baseline according to its potential for energy savings, while each DR measure was evaluated according to its potential for reducing electricity consumption in critical peak pricing (CPP) periods. All measures were evaluated in five locations, namely Miami, Las Vegas, Seattle, Chicago and Duluth, to understand the impact of climate conditions on energy savings and power demand reduction. The results showed that shortened heating, ventilation and air conditioning (HVAC) operation schedules, demand-controlled ventilation, and widened thermostat deadbands are the top three measures for site energy savings. Floating head pressure and antisweat heater controls are the two measures that reduced annual electricity consumed by refrigeration systems by between 7% and 15% in all locations except Miami. Advanced refrigeration controls for DR reduced electricity consumption during the CPP periods by about 6% for all five locations, while the DR measures based on space air-conditioning controls generated between 1% and 9% demand reduction, depending on locations and measures.

INTRODUCTION

Many commercial buildings today do not deliver the energy performance predicted by designers or expected by the owners. One of the primary reasons for excess energy consumption lies in the inability to adequately sense, monitor and control of building systems. More than 80% of commercial buildings still use time clocks, independent thermostats to control HVAC equipment or manual switching (Katipamula et al. 2012). Even the buildings that use sophisticated building automation systems usually have a number of operational problems that lead to significant increases in energy consumption. Many energy saving opportunities, especially from those control upgrades, are missed partly because relevant stakeholders such as building owners and managers are not aware of the potential impact of those control measures. Most existing studies in literature either discussed the impact of control measures qualitatively (DOE 2013a, PECI 2016) or presented the measured saving from a specific case study (DOE 2015, Fricke and Becker 2010, Levin and Paulsen 2006). A more systematic study is needed to quantify the benefits from different control strategies. This paper presents such analysis for grocery stores, which are energy-intensive buildings that consume the greatest amount of electricity per floor area of any building type in the U.S. and represent 5% of total U.S. commercial building primary energy use (EIA 2006).

To facilitate the analysis, a baseline model was developed to represent an existing grocery store built in the 1990s. A total of 19 control measures were evaluated using EnergyPlus, a whole-building simulation program that supports commercial refrigeration and its interactions with space conditioning. All measures were simulated in five locations with different climates as follows: Miami (hot and humid), Las Vegas (hot and dry), Seattle (marine), Chicago (cold) and Duluth (very cold).

BASELINE BUILDING MODEL DESCRIPTION

The baseline model originated from the Grocery Store 50% Energy Savings Technical Support Document (Leach et al. 2009) with some modifications. The prototype store is a standalone, single-story building with 4,180 m^2 of construction area. With an aspect ratio of 1.5, the store has a footprint dimension of 79.2 m by 52.8 m and a floor-to-roof height of 6.1 m, without drop ceilings. The space types captured in the building model include main sales (49.8%), perimeter sales (5.1%), produce (17.0%), deli (5.4%), bakery (5.0%), active storage (10.1%), office (0.7%), meeting room (1.1%), dining room (1.1%), restroom (1.5%), mechanical room (1.3%), corridor (1.2%), and vestibule (0.7%), where the numbers in parentheses indicate the percentage of the total building area corresponding to each space type. Figure 1 shows the store layout.

According to the opaque envelope construction types specified in ASHRAE Standard 90.1 (ASHRAE 2004a), the store uses a mass wall, insulation entirely above the deck for the roof, and a slab-on-grade floor. Regarding

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fenestration, all glazing is located on the main entrance wall. The vertical glazing accounts for about 8% of the total wall area. No skylight is used in the model. The internal thermal mass was assumed to be 19.6 kJ/°C for every square meter of floor area. Because the baseline model was created in this work to represent the existing stock of grocery stores built around the 1990s, the building envelope's thermal performance complies with the minimum requirements specified by ASHRAE Standard 90.1-1999 (ASHRAE 1999).

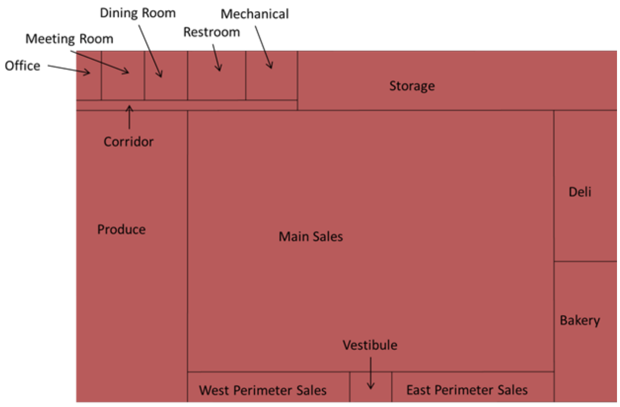

Figure 1: Floor Plan of the Modelled Grocery Store

Internal loads (e.g., occupants, lighting, and plug loads) and ventilation requirements were modelled the same as those in the original model (see Leach et al. 2009 for more details). The store operates from 6:00 am to 10:00 pm, 7 days per week. Figure 2 shows the internal load profiles for the sales areas on weekdays.

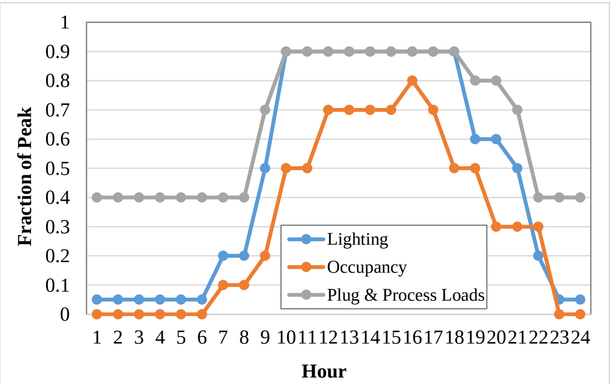

Figure 2: Weekday Internal Load Profiles for Sales

Packaged air-conditioners with gas heat were used to maintain thermal comfort in all spaces. Although it is common in the field that a large space (e.g., main sales) served by multiple packaged rooftop units (RTUs) and several small neighbouring spaces (e.g., meeting room and dining in Figure 1) are combined as a single thermal zone, all spaces in Figure 1 were modelled separately as individual thermal zones for the purpose of simplification. This simplification does not affect the simulation results because all packaged RTUs were modelled with identical characteristics: coefficient of performance (COP) of 3.47, fan efficiency of 33%, and pressure rise of 404 Pa (Hendron et al. 2012). It was assumed that the store had no active humidity controls and all packaged units ran continuously 24/7 in the baseline model. No economizer was used in all packaged systems to avoid the impact of outdoor air on the store humidity.

Direct refrigeration was the system type used in the grocery store. The store had four compressor racks: two low-temperature racks serving frozen food cases, ice cream cases, and walk-in freezers; and two medium-temperature racks serving meat cases, dairy/deli cases, and walk-in coolers. Overall, there are a total of 7 low-temperature cases, 19 medium-temperature cases, 2 walk-in freezers, and 8 walk-in coolers.

BASELINE MODEL BENCHMARKING

It must be recognized that the baseline model was not developed for a specific grocery store. Therefore, benchmarking a prototype model is a challenge because there are so many design variables (e.g., construction, internal loads, operation schedules, and HVAC systems) that could affect the whole building energy use. The focus here is to provide a clear picture of the energy end uses in the baseline model, rather than calibrating the prototype model to match any specific energy use intensity (EUI). However, particular attention was given to the refrigeration system because 1) refrigeration accounts for the largest fraction of electricity consumption in grocery stores (EIA 2006); and 2) many measures in this work are related to the refrigeration system controls.

Figure 3 shows the baseline EUI in the five locations. Of the seven energy end uses, cooling, lighting, fan, and refrigeration use electricity; heating and service hot water use natural gas; while plug and process use both electricity (e.g., office equipment and miscellaneous plug loads) and natural gas (e.g., cooking equipment). Electricity and natural gas energy are not distinguished in reporting onsite energy uses in Figure 3. The Figure shows the following:

- The baseline EUI ranged from about 3,300 MJ/m^2/yr (290 kBtu/ft^2/yr) in Miami to 5,730 MJ/m^2/yr (505 kBtu/ft^2/yr) in Duluth. As a reference, the national average EUI for grocery stores is 2,430 MJ/m^2/yr (214 kBtu/ft^2/yr) (EIA 2006), which is much lower than the baseline model. The EUI difference between the baseline and the national average might be attributed to several factors: 1) the national average covers many stores with varied climate conditions, operational schedules, and the number of refrigeration cases, all of which affect the EUI significantly; 2) the baseline model represents a not well-maintained store that has a number of operational faults; and 3) some of the baseline assumptions may be different from the prevalent practices.
- Space heating contributed a large portion of whole-building EUI for all locations except Miami. The calculation showed that space heating accounted for

22% of the whole-building energy use in Las Vegas, 38% in Seattle, 43% in Chicago, and 51% in Duluth. In contrast, the national average data (EIA 2006) showed that only 14% of grocery store energy use is for space heating. Possible causes of the large fraction of space heating in the baseline include 1) no heat recovery was captured in the model; and 2) the outdoor-air flow rate for ventilation was calculated according to ASHRAE 62.1 (ASHRAE 2004b), which may not be strictly followed by most existing buildings.

- Refrigeration is the largest energy end use in Miami (35%) and Las Vegas (29%) while it is the second largest energy end use in the other three locations (23% in Seattle, 21% in Chicago and 18% in Duluth), where the numbers in parentheses are the percentages of building energy for refrigeration. With respect to the building electricity consumption, refrigeration represented a higher fraction. The calculation showed that refrigeration consumed around 46% of whole building electricity for all locations.

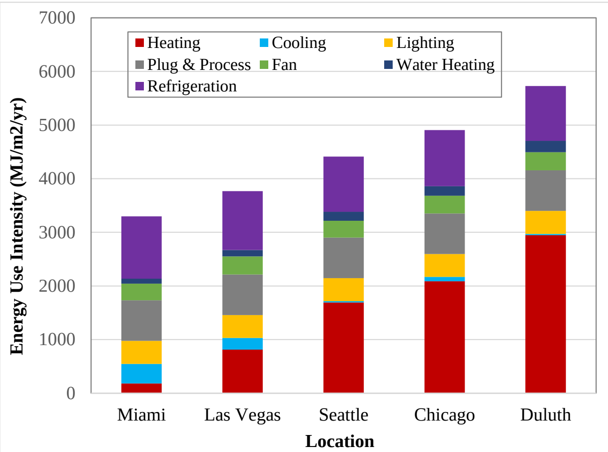

Figure 3: Baseline Energy Use Intensities

A closer look at the refrigeration energy end uses showed that 1) low-temperature cases and walk-ins used 55% of the refrigeration electricity while medium-temperature cases and walk-ins used the remaining 45%; and 2) refrigerated display cases used 86% of the refrigeration electricity while walk-ins used the remaining 14%. Based on the average of all five locations, Figure 4 shows the detailed decomposition of energy end uses for refrigerated cases. As expected, compressor and condenser fans accounted for the largest fraction of refrigeration system electricity. Antisweat heaters were another large energy use for low-temperature cases, contributing 35% of refrigeration electricity. The breakdown of electricity consumption in the refrigeration system is consistent with the literature (Goetzler et al. 2009).

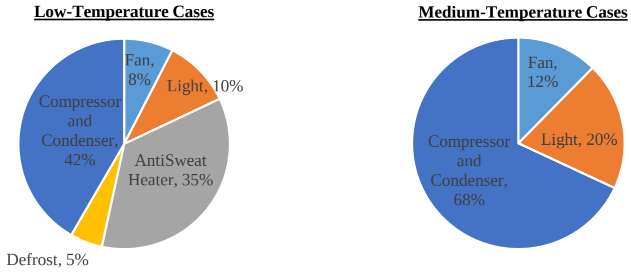

Figure 4: Breakdown of Refrigeration System Electricity

CONTROL MEASURES SIMULATED

A total of 19 control measures were investigated in this work including 15 energy efficiency (EE) measures and 4 demand response (DR) measures. The EE measures intend to reduce energy consumption while the DR measures intend to reduce the peak electric demand. These measures are briefly discussed below. More details on their implementation in EnergyPlus can be found in Fernandez et al (2016).

Energy Efficiency Measures

Fix Low Refrigerant Charge for Packaged Rooftop Units (EE1). The baseline assumed that the refrigerants in all packaged RTUs were 20% under charged, a consequence of either initial undercharging of refrigerant or refrigerant leakage through the unit operation. According to Kim and Braun (2010), packaged air conditioners with 20% refrigerant undercharging reduces the cooling efficiency by 10% and the cooling capacity by 20% relative to the units with correct refrigerant charge. Under this measure, packed air conditioners were recharged to the proper level and the cooling efficiency and the cooling capacity were restored to the design level.

Shorten HVAC Operation Schedules (EE2). The baseline had HVAC systems continuously running even though the store operation hours are from 6:00 am to 10:00 pm. Such schedule mismatch between HVAC system operation and store business operation is a frequently observed phenomenon in the field, which is possibly due to conservative facility management strategies or inappropriate system setup and maintenance. This measure corrected the HVAC operation schedule to be from 4:00 am to 11:00 pm, considering the necessary time for space warm up or cool down, grocery night stocking, cleaning and maintenance. In the EnergyPlus simulation, the measure involves the change of fan schedules, thermostat set point schedules, and infiltration schedules. For example, the thermostat set points were changed from 21.7°C to 18.3°C for heating and from 22.8°C to 26.7°C for cooling during scheduled system off hours.

Outdoor-Air Damper Control Upgrade (EE3). The baseline assumed the outdoor-air (OA) damper was open for a constant OA flow rate if the system runs during non-business hours. In contrast, under this measure, the OA damper closed during non-business hours (including early morning warm up and cool down periods).

Widened Thermostat Deadbands and Night Setback (EE4). In the baseline, all spaces had thermostat set points at 21.7°C for heating and 22.8°C for cooling. No temperature set back was used. Under this measure, the thermostat set points were widened to 20.6°C for heating and 23.9°C for cooling. If this measure was used in combination with the measure of shortening HVAC operation schedules discussed previously, the heating set point would be set back further to 15.6°C during the scheduled system off periods.

Demand-Controlled Ventilation (EE5). The baseline assumed that each packaged RTU supplied outdoor air at the design flow rate that satisfies the ventilation needs for the peak number of occupants. In this work, the measure was implemented with a CO_2-based approach, which adjusts the amount of outdoor air for each RTU to maintain the CO_2 concentration below 1000 ppm for the space that each RTU serves.

Occupancy Sensors for Interior Lighting (EE6). The baseline assumed that all interior lighting for space illumination was manually controlled with a nighttime sweep. After applying this measure, occupancy sensors were installed to control general lighting in the following spaces: offices (33%), meeting rooms (43%), restrooms (26%), dining rooms (22%), mechanical rooms (40%), and active storage areas (40%), where the numbers in parentheses indicate the percentage of lighting energy savings from occupancy sensor control for the corresponding spaces (Thornton et al. 2009). This measure was simulated by adjusting the baseline lighting schedules in applicable spaces according to the anticipated percentage of lighting energy savings.

Parking Lot Lighting Control (EE7). The design lighting power for exterior parking lots was calculated to be 10.94 kW based on the lighting power allowance (ASHRAE 1999) and the parking areas calculated from the government guidelines (City of Houston 2016, City of Red Oak 2016). In the baseline, parking lot lights were controlled on and off according to an astronomical clock that simulates the use of a photocell. This keeps the lights strictly on at night and strictly off during the day. The advanced control measure intends to reduce the lighting energy for unoccupied parking lots overnight. The measure still used a simulated photocell to shut parking lot lights off during the day. At night, however, parking lot lights were on at the design level during store business hours plus an additional hour before and after store operation, but the lights were reduced to 25% of the design level outside of the above time window (e.g., leaving one out of four lights on for safety reasons).

Advanced RTU Controls (EE8). In the baseline, all RTUs were equipped with constant-speed supply fans. Thus, the supply fan runs at its full speed regardless of the RTU's mode of operation. Advanced RTU controllers that modify the supply-fan speed based on the units' mode of operation are commercially available and were reported to have large energy savings (Wang et al. 2013). Under this measure, the supply fans run at 40% of full speed during the ventilation mode, 75% during the economizer only mode, and 90% during both heating mode and cooling mode.

Refrigerated Case Lighting Controls (EE9). In the baseline, all case lights, if exists, were on continuously, even during off-business hours. Under this measure, case lights were shut off during the period from 1 hour after the store closes until 1 hour prior to the store opening (i.e., 11:00 p.m. to 5:00 a.m. 7 days per week). These two 1-hour time windows intended to be used for stocking and possible display case checkup.

Walk-In Lighting Controls (EE10). Both the baseline and the control measure were implemented the same as the aforementioned case lighting controls, except that the target was to improve lighting controls in walk-ins instead of refrigerated cases.

Refrigeration Floating Head Pressure (EE11). The baseline assumed the use of constant-speed condenser fans cycling on and off to maintain the saturated condensing temperature at 26.7°C. In contrast, floating head pressure control intends to reduce the head pressure at low ambient-air temperature conditions. To float head pressure, the condenser fans are usually required to operate continuously instead of cycling on and off. Thus, the air-cooled condenser may need to be retrofitted with variable-speed drives (VSDs) to implement this measure. Floating head pressure was simulated in this work by 1) dynamically setting the saturated condensing temperature to be 5.6°C offset from the outdoor-air temperature for the two low-temperature refrigeration systems and 8.3°C offset for the two high-temperature refrigeration systems (ASHRAE 2015), but no lower than 15.6°C; and 2) controlling all condenser fans in unison (i.e., the same speed) through the use of VSDs. As one of the most effective energy efficiency measures for commercial refrigeration, floating head pressure can save 2% compressor energy per one degree of reduction in condensing temperature (ASHRAE 2015).

Refrigeration Floating Suction Pressure (EE12). Fixed suction control was assumed in the baseline model. This means that for a given compressor rack, a fixed pressure set point was maintained constantly to meet the possible cooling loads at the most favourable conditions (e.g., peak indoor temperature and shopper traffic). With this measure, the suction pressure of a compressor rack was automatically adjusted such that the pressure is no lower than necessary to keep the contents of the refrigerated case at the desired temperature, given current operating conditions. Operating at a higher suction pressure saves energy by reducing lift and compressor power.

On-Demand Defrost Control (EE13). This measure intends to save the electric energy used for defrosting refrigerated display case evaporators. In the baseline, the medium-temperature display cases accomplished defrosting by simply interrupting the refrigerant flow to the evaporator periodically while keeping the evaporator fan continuously running. There is no energy penalty from this defrost strategy, so these medium temperature cases were not targeted with this measure. The low-temperature display cases, however, accomplished defrosting by energizing electric resistance heaters for a fixed length of time with a predetermined schedule. Because the time length for defrosting was determined from the worst-case design, unnecessary defrost cycles and excessively long defrost cycles occur throughout the display case operation. Many on-demand defrosting technologies exist (Fricke and Sharma 2011) to initiate a defrost cycle whenever sufficient ice accumulation happens and to terminate a defrost cycle as soon as the ice is completely melted. This work modelled a “time-temperature control” strategy that uses a temperature sensor on the evaporator to determine when the frost has melted and the defrost cycle can be terminated. This on-demand defrosting control was applied to seven low-temperature refrigerated display cases and five walk-ins that use electric resistance for evaporator defrost.

Antisweat Heater Control (EE14). This measure simulates an advanced control strategy for antisweat heaters, which are heating strips that prevent moisture from condensing and accumulating on the glass doors and frames of low-temperature refrigerated display cases. In the baseline, antisweat heaters ran continuously at the design power, regardless of the ambient conditions in the store. Advanced antisweat heater controllers were used to adjust the heat needed according to the ambient air dewpoint temperature around display cases. As shown in Equation 1, the actual antisweat heater power (P) is calculated as (DOE 2013b):

$$P = P_{rated} * (T_{dp,air} - T_{case})/(T_{dp,rated} - T_{case}) \qquad (1)$$

where, P_{rated} is the rated antisweat heater power (W); $T_{dp,rated}$ and $T_{dp,air}$ respectively represents the rated and the actual ambient dewpoint (°C); and T_{case} is the case operating temperature (°C).

Walk-In Fan Speed Control (EE15). This measure saves energy by reducing fan power in walk-in coolers and walk-in freezers. In the baseline, the walk-in fan motor ran continuously at full speed, even if the corresponding walk-in thermostat called for partial cooling or no cooling at all. Under this measure, the evaporator fan motor speed modulates based on the position of the expansion valve position. When the valve is greater than 50% open, the fan motor runs at 100%, and when the valve is less than 50% open, the fan motor reduces to 80% speed (ASHRAE 2015). In the model, the valve position was estimated by the evaporator’s actual cooling rate as a percentage of its design capacity.

Demand Response Measures

DR events were defined in this work as critical peak pricing (CPP) periods in 4-hour windows from 2:00 p.m. to 6:00 p.m. during the eight hottest weekdays of the year in each location. The following four DR measures were considered to reduce electricity power in CPP periods.

Cooling Set Point Reset (DR1). This measure adjusts the cooling set point temperature for all spaces during a CPP event. The set point changes entailed raising the cooling thermostat set point from 22.8°C to 25.8°C immediately coincident with the start of the CPP event, then releasing the thermostat set point to its normal value at the end of the event.

Space Pre-Cooling (DR2). This measure responds proactively by pre-cooling the building 3 hours ahead of the CPP event to below normal set points. The precooled thermal masses are expected to shift the peak cooling load out of the CPP event. The pre-cooling strategy was implemented by a stepwise reduction in the cooling set point. Within 3 hours before the occurrence of CPP event, the cooling set point was reduced from 22.8°C to 19.8°C at the rate of 1°C reduction per hour.

Duty Cycle (DR3). This measure reduces the electricity consumption by limiting the number of packaged RTUs that can operate during the CPP events. To implement this measure, all RTUs were evaluated with their cooling capacity and the DR capability, which led to three RTU groups. Group 1 includes the RTUs that serve main sales; Group 2 includes the RTUs that serve perimeter sales and produce; and Group 3 includes the RTUs that serve the corridor, restroom, mechanical room, active storage, dining room, meeting room and office (see Figure 1). These RTUs were grouped to have similar cooling capacities and thus similar power consumption. A balanced power grouping strategy is favourable for the implementation of duty cycling. Note that the two RTUs serving the bakery and deli were not involved in the duty cycle control because those spaces had large exhaust fans running during the CPP event and the RTUs were needed to provide make-up air. The three groups of RTUs ran alternatively for every hour during a CPP event.

Refrigeration System Load Controls (DR4). This measure combines the following strategies together during the CPP events: 1) suspend the defrost cycles; 2) shut off the refrigerated case lighting; and 3) shut off the antisweat heaters. Implementing these strategies during the CPP events does not compromise the refrigerated product quality.

RESULTS AND DISCUSSION

This section presents the simulation results for individual measures as well as a few packages of measures, which are discussed later. For each EE measure, the energy savings relative to the baseline is presented. For each DR measure, the average reduction of power demand relative to the baseline during all CPP events is presented.

Results for Individual Energy Efficiency Measures

Table 1 provides the percentage of onsite energy savings for all EE measures relative to the baseline. This table leads to the following major observations:

- Of the 15 EE measures, EE2 (shorten HVAC operation schedules), EE5 (DCV), and EE4 (widen thermostat deadbands) were the top three measures that had the largest onsite energy savings. These three measures respectively reduced the baseline EUI by between 4.6% and 10.2%, between 2.1% and 11.6%, and between 4.6% and 6.0%, where the ranges indicate the results for the five locations.
- Of the seven refrigeration measures (EE9-EE15), EE11 (floating head pressures) had the largest energy savings. It reduced the baseline EUI by 0.9% in

Miami, 3.2% in Seattle, and 2.6% in each of the other three locations.

- EE8 (advanced RTU controls) and EE1 (fix RTU low refrigerant charging problem) had noticeably more impact in Miami than other locations. Because a measure can reduce cooling or fan energy but also increase heating energy, the impact sometimes varies significantly with locations. This can be more clearly demonstrated through a split analysis of electricity and natural gas consumption due to measure implementation, as discussed next.

Table 1: Percentage of Energy Savings for Energy Efficiency Measures

Measure	Miami	Las Vegas	Seattle	Chicago	Duluth
EE1	0.5%	0.3%	0.1%	0.1%	0.0%
EE2	4.6%	7.5%	9.7%	9.5%	10.2%
EE3	0.1%	0.1%	0.1%	0.2%	0.3%
EE4	4.7%	4.9%	6.0%	5.1%	4.6%
EE5	2.1%	5.4%	9.5%	10.0%	11.6%
EE6	0.3%	0.2%	0.0%	0.1%	0.0%
EE7	0.3%	0.3%	0.2%	0.2%	0.2%
EE8	3.1%	1.8%	0.2%	0.5%	0.0%
EE9	0.6%	0.6%	0.4%	0.4%	0.3%
EE10	0.1%	0.1%	0.1%	0.1%	0.1%
EE11	0.9%	2.6%	3.2%	2.6%	2.6%
EE12	0.1%	0.1%	0.1%	0.1%	0.1%
EE13	0.3%	1.0%	0.7%	0.6%	0.6%
EE14	0.3%	2.4%	1.2%	1.3%	1.5%
EE15	0.2%	0.2%	0.2%	0.2%	0.1%

Figures 5 and 6 are stacked bar charts showing the impact of all EE measures on electricity and natural gas, respectively, in Miami and Chicago. In these two figures, the blue bars represent the electricity savings while the red bars represent the natural gas savings. Both electricity and natural gas savings were calculated as the percentage of the whole-building energy use. In equations, they are expressed as:

$$ElecPercent = \frac{Elec_{base} - Elec_i}{BldgEnergy_{base}} * 100\% \quad (2)$$

$$GasPercent = \frac{Gas_{base} - Gas_i}{BldgEnergy_{base}} * 100\% \quad (3)$$

where, *ElecPercent* and *GasPercent* are the percentages of electricity savings and gas savings in Figures 5 and 6; *BldgEnergy* is the whole-building energy use; the subscripts i and *base* stand for the i-th measure and the baseline. Because Equations 2 and 3 have the baseline building energy as their denominators, the sum of *ElecPercent* and *GasPercent* for a given measure and location is equal to the corresponding value in Table 1.

Major findings from Figures 5 and 6 include:

- EE8 (advanced RTU controls) led to electricity savings from fan speed modulation but also led to a penalty on heating because of the reduced heat gains dissipated by the fan motor. There is more net positive impact in locations with a hot climate (e.g., Miami) than other locations (e.g., Chicago). This observation was reported previously in Wang et al. (2013).
- The top three measures (i.e., EE2, EE5 and EE4) on energy savings in Table 1 were significantly different with respect to the sources of energy savings. Electricity savings dominate in Miami while gas savings dominate in Chicago. Because of this, Chicago had higher overall savings than Miami, as observed in Table 1.

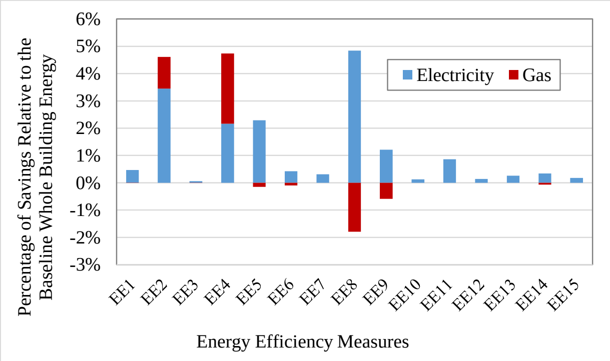

Figure 5: Impact of Energy Efficiency Measures on Electricity and Gas Consumption in Miami.

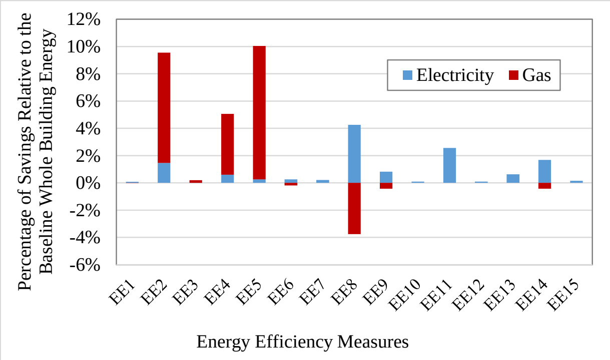

Figure 6: Impact of Energy Efficiency Measures on Electricity and Gas Consumption in Chicago.

Because refrigeration is a major energy end use in grocery stores and many simulated measures are for the refrigeration system, it is worthwhile to closely investigate the refrigeration measures. Recall from Figure 4 that the refrigeration system energy end use includes the energy consumed by compressors and condenser fans, and the energy for lighting, evaporator fans, antisweat heaters, and defrosting in both display cases and walk-ins. Table 2 shows the impact of all 7 refrigeration measures. This table indicates the following:

- Floating head pressure (EE11) had the largest savings on refrigeration system energy. Relative to the baseline with constant head pressure control, this measure saved 2.4%, 9.0%, 13.9%, 12.0%, and 14.7% of refrigeration system energy, respectively in Miami, Las Vegas, Seattle, Chicago, and Duluth. If only the energy by compressors and condenser fans was considered, the percentage of energy savings would be roughly between 4.2% and 28.3%, which was derived from the energy decomposition of refrigeration system energy, shown in Figure 4. The results align with the estimation in literature (Singh 2006) that indicated 14% savings of the combined compressor and condenser energy in Atlanta, GA.
- Antisweat heater control (EE14) also had a relatively large impact on refrigeration system energy consumption in all locations except for Miami. Relative to the baseline with antisweat heaters running continuously, the advanced control that energizes antisweat heaters only when the threat of condensation is present reduced the whole refrigeration system energy consumption by 10.1%, 6.9%, 8.0%, and 11.0%, respectively, in Las Vegas, Seattle, Chicago, and Duluth. These values are equivalent to between 0.3% and 2.4% savings of the baseline whole-building energy. The results are consistent with the report (EPA 2010) indicating that compared to the baseline supermarket energy, approximately 2% savings can be achieved from antisweat heater controls on glass door cabinets.
- Turning off lights in both refrigerated cases and walk-ins during non-business hours (EE9 and EE10) reduced the whole refrigeration system energy consumption by about 4% for each of the five locations.
- Relative to a scheduled defrosting strategy in the baseline, on-demand defrosting (EE13) saved between 0.7% and 3.6% of refrigeration system energy. This impact is significant considering that electric defrosting is used only in low-temperature cases and walk-ins, which account for only 55% of the total refrigeration system energy consumption. The results align with a case study that reported 9% energy savings on frozen cabinets from the use of on-demand defrost controls (EPA 2010).
- Floating suction pressure (EE12) and walk-in evaporator fan speed control (EE15) were the two measures that have the least impact (<1%) on the refrigeration system energy.

Table 2: Percentage of Refrigeration System Energy Savings from Refrigeration Measures

Measure	Miami	Las Vegas	Seattle	Chicago	Duluth
EE9	3.4%	3.7%	3.9%	3.8%	3.9%
EE10	0.4%	0.4%	0.4%	0.4%	0.4%
EE11	2.4%	9.0%	13.9%	12.0%	14.7%
EE12	0.4%	0.4%	0.5%	0.5%	0.5%
EE13	0.7%	3.5%	3.0%	2.9%	3.6%
EE14	1.0%	10.1%	6.9%	8.0%	11.0%
EE15	0.5%	0.7%	0.7%	0.7%	0.8%

Results for Individual Demand Response Measures

The DR measures were evaluated with respect to the change of electricity consumption during the DR periods. In Equation 4, the impact of each DR measure was estimated as:

$$PD = \left(1 - \frac{\sum_j Elec_{DR}}{\sum_j Elec_{base}}\right) * 100\% \quad (4)$$

where, PD represents the percentage of power reduced relative to the baseline; the subscripts $j, DR, base$ stand for each hour in the CPP events, DR measure, and the baseline, respectively. Figure 7 shows the results for DR measures. This figure shows that relative to the baseline without any DR strategies:

- Increasing the cooling set point (DR1) decreased the electricity consumption in the DR periods by between 5% and 8% in Miami, Las Vegas, and Duluth, but only by 2% in Seattle.
- Space pre-cooling (DR2) had a slightly stronger impact than DR1. Via pre-cooling, the electricity consumption was decreased by between 6% and 9% in Miami, Las Vegas, and Duluth, but only by 3% in Seattle.
- Duty cycling of RTUs (DR3) yielded a reduction between 1% and 3% in electricity consumption during the DR periods for all locations.
- In contrast with the previous three DR measures whose impact depends on the climate (e.g., Seattle does not have much cooling even during the DR periods), the refrigeration control (DR4) had relatively constant (i.e., around 6%) impact on power reduction across the five locations. Note that in the baseline, no defrosting cycles fall into the DR periods. The impact of DR4 would be even higher if some defrosting cycles were originally scheduled during the afternoon when CPP events normally occur.

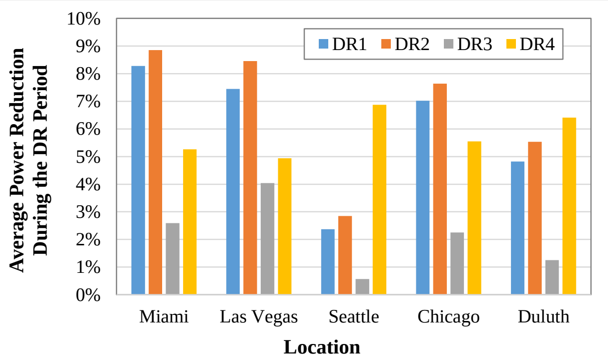

Figure 7: Electricity Power Reduction from Demand Response Measures

Results for Energy Efficiency Packages

In many cases, building operators and managers are more willing to deploy a package of synergistic measures rather than individual ones for the purpose of a better rate of return. Based on previous experience of building re-tuning (e.g., Fernandez et al. 2016), we created the following three packages:

- Package A: EE1, EE6, EE9 and EE10
- Package B: Measures in Package A plus EE2, EE3, EE4, EE5, EE7, EE11, and EE14
- Package C: All measures

Package A pertains to a package of easy-to-implement measures for a typical grocery store. Package B includes several other measures that take more efforts to implement but have more impact on energy savings. Finally, Package C includes all measures, including several additional measures that require small capital investment.

Figure 8: Percentage of Energy Savings from Packaged Measures

Figure 8 shows the simulated results of energy savings from the proposed three packages:

- Package A achieved minor savings relative to the baseline, ranging from 0.55 to 1.5%.
- Package B had much higher energy savings than Package A. The percentage of savings ranged from 14% in Miami to 29% in Duluth.
- Relative to Package B, Package C led to minor additional savings, ranging from 1% in Duluth to 4% in Miami.

CONCLUSIONS

This paper used EnergyPlus to evaluate the potential energy savings of 15 energy efficiency measures and the potential power reduction of 4 demand response measures. All of these measures can be implemented with small or even no capital investment. The simulated results showed that shortened HVAC operation schedules, demand-controlled ventilation, and widened thermostat deadbands are the top three measures that can each achieve more than 4% whole-building energy savings in most locations. In cold climates, most of the above energy saving comes from natural gas for heating. Floating head pressure and antisweat heater controls are the two measures that can each reduce between 7% and 15% of annual electricity consumption by the refrigeration system in all locations except for Miami. Combining all energy efficiency measures together resulted in energy savings from 18% in Miami to 30% in Duluth. Advanced refrigeration controls for DR reduce electricity consumption during the CPP periods by about 6% for all five locations while the DR measures on air conditioning generate between 1% and 9% demand reduction, depending on locations and measures.

Future work to be considered includes 1) a closer investigation of the heating energy use and the heating system in real grocery stores and the baseline models; and 2) consideration of additional measures such as upgrading case lights to LED, heat recovery from refrigeration systems for space heating, adding glass doors to open cases, and improved make-up air flow organization.

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