Frozen Freedom: Unleashing Grocery Store Demand Flexibility

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ABSTRACT

Grocery stores consumed approximately 3% of total electricity used by commercial buildings in the United States in 2018 (EIA 2018), representing a unique end-use load profile characterized by the critical use of refrigerated display cases. Exploring demand response (DR) scenarios in grocers presents an opportunity to enhance the efficiency, resilience, and sustainability of surrounding communities. In addition, recent studies demonstrate that implementing control algorithms considering demand flexibility strategies can lead to load and peak reductions in stand-alone refrigerated display cases. Because small business grocery stores operate on thin margins, energy bill savings from DR could make a positive difference toward continued operations.

Still, uncertainty remains about the extent of what demand flexibility potential controls could provide when coupling refrigeration with whole-building operation. To enhance economic viability and grid stability, it is essential to quantify the load flexibility capability of grocery stores. Advanced controls can optimize energy consumption by responding to load shedding, shifting, and DR events, as well as daily time-of-use (TOU) rates without compromising food safety.

Using both quantitative data and interviews with community-based organizations, we developed a full-size store model and two smaller store models with controlled refrigerated cases, HVAC, and lighting systems based on actual grocery store properties. Through simulations, we have assessed load flexibility strategies with varied DR events. The results highlight trade-offs for DR potential, energy, and peak demand with advanced or basic controls. However, interviews and data indicate that more support is needed to make DR strategies consistently accessible to small grocery stores.

Introduction

As business and industry transition to cleaner and more efficient energy usage, creating decarbonization pathways for a wider array of organizations will ensure that small businesses are not left behind by advancing regulation and technological frontiers. Grocery stores are often overlooked as potential sources of demand flexibility, especially if they are smaller sized, because of a lack of understanding of their potential benefits. This study investigates the potential energy savings of demand response (DR) scenarios in both large and small grocery stores.[1]

Food purchases are the third largest U.S. consumer spending category behind housing and transportation, representing 13% of household expenditures (Zeballos, Dong and Islamaj 2023). The grocery industry is also characterized by massive energy consumption. Food retail organizations have one of the highest energy use intensity (EUI) rates among commercial building types (ESPM 2023). Grocery stores account for 63% of energy consumption in the food sales industry; in addition, they are responsible for approximately 3% of major fuels consumption by commercial buildings in the United States (EIA 2018).

Considering the composition of grocery store energy usage, refrigeration systems could be responsible for 40%—60% of a supermarket's electricity consumption (Klemick, Kopits, and Wolverton 2015). After refrigeration, the second-largest share is space heating and cooling, which account for 17% of grocery stores' major fuel energy consumption (EIA 2018). Successful refrigeration operations are essential for all grocery stores, given that keeping perishable products below required temperatures is a regulated health and safety issue. Power outages or failed equipment can cost grocery stores massive revenue in lost product and/or labor costs required to save perishables during outages (Hawthorne 2024).

Implications For Disadvantaged Communities

Due to the slim margins on which many small businesses operate, a reduced energy bill can provide budget relief and lower energy burden for a small business. Supporting continued small grocery operations in disadvantaged communities (DACs)[2] ensures that energy burdened households have access to basic needs. The continuity of grocery operations plays a part in preventing the formation of food deserts, defined as geographic areas with limited access to affordable and nutritious food and limited transportation options. In urban settings, geographic areas with higher levels of poverty and higher concentrations of racial minority residents are more likely to be food deserts (USDA 2009; Dutko, Ver Ploeg, and Farrigan 2012).

This paper explores how DR could benefit both large grocery stores and grocery stores with a small square footage. Although a small-sized grocery store might exist in a middle- or upper-income area, low-income areas tend to contain fewer midsized or large stores than other areas; in general, grocery stores in low-income areas have smaller square footage (Brookings

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[1] A detailed definition of the difference between a small grocery store and a convenience store is outside the scope of this project. To differentiate at a high level, we consider small grocery stores to have smaller square footage than full-sized grocery stores and sell a variety of products including produce, meat, and dairy. Convenience stores are small stores that do not sell all three of the above products and are often connected to fast food and/or gasoline sales. This differentiation is based on the Food Marketing Institute and Ohri-Vachaspati et al. (2019).

[2] To define "disadvantaged communities," we utilized the Climate and Economic Justice Screening Tool (CEJST). The CEJST identifies disadvantaged communities according to their location within or in proximity to eight categories of burden, which include energy and transportation.

2006). Regions with a larger percentage of households using public assistance have fewer stores as well as less selling space per capita (Cotterill and Franklin 1995). By studying the DR potential of both large and small stores, this paper considers grocers across the economic spectrum.

Methodology

In this paper, we applied setpoint changes to heating, ventilation, and air-conditioning (HVAC) and commercial refrigeration equipment in building energy models to study the DR potential for various time durations for three types of grocery stores: a full-size store, an energy-efficient small store, and a high-energy small store.

We determined the setpoint changes in two ways:

1. Advanced control: a custom National Renewable Energy Laboratory (NREL)-developed algorithm designed to reduce the energy consumption during a DR event by controlling setpoints for HVAC and refrigeration. This included pre-cooling or pre-heating before the event and coordinating assets while maintaining occupant comfort and product quality.
2. Basic control: a manual approach that involved changing setpoints when the DR event starts, with no preparation (no pre-cooling or pre-heating) and no coordination of assets during the event.

We will first discuss the three building energy models used to perform this study, then showcase the DR simulations performed. We will then present results from the simulations and discuss the DR potential of each grocery store type. All modeling was performed using the building simulation engine EnergyPlus with actual meteorological weather data for the year 2012 from the Rocky Mountain Metropolitan Airport, located in Broomfield, Colorado, USA (part of the Denver metropolitan area). We selected this location because of the location of NREL and one of the community-based organizations (CBOs) we interviewed.

Full-Size Grocery Store Building Energy Model

This study used the full-size grocery store building energy model developed for the *Advanced Energy Design Guide (AEDG) for Grocery Stores: Achieving 50% Energy Savings Toward a Net Zero Energy Building* (ASHRAE 2015). The AEDG offers the tools needed for achieving a 50% energy savings as compared to buildings that meet the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004.[3] The 50% AEDG for Grocery Stores is meant for grocery stores ranging in size from 25,000 to 65,000 ft² with medium- and low-temperature refrigerated cases and walk-ins.

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[3] The entire 50% AEDG series used ANSI/ASHRAE/IESNA Standard 90.1-2004 as the baseline for comparison such that there was uniformity amongst the guides. ANSI/ASHRAE Standard 62.1-1999, mentioned on the following page, was the companion to Standard 90.1-2004 and thus also used to design this AEDG.

For the 50% AEDG for Grocery Stores, the model from Leach et al. (2009) was used as a starting point to help define certain building characteristics that were not code regulated. The space types represented in this model include back-of-house (storage); bakery; break/meeting rooms; corridors; deli; mechanical rooms; offices; produce; restrooms; sales areas; and vestibules.

The grocery store model was 45,000 square feet with an aspect ratio of 1.5 and a ceiling height of 20 ft. The mass walls were made of concrete block with R-7.6 continuous insulation, and the roof was built up with R-15 insulation entirely above deck and an ethylene propylene diene terpolymer membrane. It had 1,400 square ft of 3.6 sill height, U-0.57, SHGC-0.49 windows, for an 8.1% window-to-wall ratio. Operating hours were assumed to be 6 a.m. to 10 p.m. daily.

Whole-building averaged internal gains are 8.6 occupants per 1,000 ft^2, 1.5 W/ft^2 of lighting, 0.88 W/ft^2 of plug loads, and 0.38 W/ft^2 of natural gas (cooking) loads. Ventilation rates by zone were defined according to ANSI/ASHRAE Standard 62.1-1999, depending on space type. Each zone in the full-size grocery store energy model was conditioned with rooftop units (RTU) comprised of a 0.8HP/1,000CFM constant-volume supply air fan, an 80% efficient natural gas-fired furnace, and a 10.1 EER direct-expansion (DX) air conditioner.

The commercial refrigeration system within the full-size grocery store model consisted of 26 refrigerated cases and 10 walk-in coolers/freezers. There were four suction groups, the first with 152 linear feet of critical low-temperature cases totaling 97,982 Btu/hr, the second with 135 linear feet of doored low-temperature cases totaling 82,469 Btu/hr, the third with 208 linear feet of open vertical medium temperature dairy/deli/meat/service cases totaling 285,565 Btu/hr, and the fourth with 244 linear feet of open vertical produce and doored prepared foods/beverage cases totaling 282,811 Btu/hr. In all, there were 739 linear feet of cases totaling 728,847 Btu/hr.

Small Grocery Store Building Energy Models

To represent smaller grocers that may occupy a portion of a strip mall or similar retail area, we developed two simpler “shoebox” grocery store models. Copeland assisted in providing inputs for these models. This work does not include a model for small business grocers with large square footage, which may have a different energy footprint from our full-sized model. To represent varying economic capabilities, we built a model for a small-sized grocery with efficient equipment, and a “high-energy” small-sized grocery that includes less efficient equipment.

Context provided from informal interviews. To inform the two small store models and independent variables, we conducted interviews with CBOs that support operational sustainability in small businesses. These CBOs indicated that small businesses, especially those in DACs, tend to have older equipment and carry out maintenance less frequently (Oliker and Otero 2024; Hawthorne 2024). Based on qualitative and quantitative data from the CBOs, our independent variables included advanced and basic controls and EUI.

Small grocery store characteristics. We developed a single zone building energy model with dimensions of 56 ft x 42 ft, at 14 ft 4 in. tall. Only one of the 42 ft walls was exposed (e.g., had an outdoor boundary condition facing east); the other three walls were modeled as adiabatic to represent being a part of a shared space. The roof was modeled as being exposed to the outdoors. All the walls were assumed to be concrete. This model also had a 2-ft crawlspace. The model was conditioned with a 7.5-ton DX air conditioner and an 80% efficient natural gas furnace. The thermostat setpoint boundaries were 71°F for heating and 73°F for cooling for the baseline and 68°F and 76°F for the basic and advanced control. 1 W/ft² of lighting was added and 300 CFM of ventilation was included. The R-134a refrigeration system included two 3-door reach-in low-temperature cases (3,065 Btu/hr at -18°F), an 8 ft medium-temperature open case (12,152 Btu/h at 23°F), and a 5-door reach-in medium-temperature case (2245 Btu/h at 28°F). The refrigeration system was a cascade type, with the low-temperature cases rejecting their heat to the medium temperature system, and the medium-temperature system rejecting its heat to the ambient via an air-cooled condenser.

High-energy small grocery store characteristics. To create this model, we changed elements of the above small store model, starting with the capacity of the refrigerated cases. The two 3-door reach-in low-temperature cases were increased from 3,065 Btu/hr to 4,950 Btu/hr, the 8 ft medium-temperature open case was reduced from 12,152 Btu/h to 11,993 Btu/h, and the 5-door reach-in medium-temperature case was increased from 2,245 Btu/h to 5,368 Btu/h. In addition, the two 3-door reach-in low-temperature cases were increased from 53 W to 165 W (fans) and 55 W to 233 W (lights), the 8 ft medium-temperature open case was increased from 33 W to 105 W (fans) and 99 W to 178 W (lights), and the 5-door reach-in medium-temperature case was increased from 66 W to 125 W (fans) and 88 W to 278 W (lights). Finally, for the two 3-door reach-in low-temperature cases only, the anti-sweat heater power was increased from 0 W (e.g., no-heat doors) to 909 W and the defrost heater power was increased from 1,188 W to 2,869 W.

Selection of Demand Response Days

Five DR days were selected to provide a statistical sample of DR potential. The hottest non-weekend days were selected for the summer. For the winter, the coldest non-weekend winter day was selected. Additionally, we examined two sequential demand response days as they were the hottest two non-weekend days for the AMY 2012 data.

Modeling Matrix

Table 1 describes the key independent variables. DR duration was run at 1, 2, and 4 hours for each permutation. DR events started at 6 a.m. and 2 p.m. for the winter and summer events respectively. EUI had two levels: average or high, based on interviews from CBOs indicating small grocers likely have higher EUI. The modeling matrix shown in Table 1, in addition to 3 different demand response durations and 6 days with demand response events, resulted in a total of 108 runs presented in the subsequent sections.

Table 1: Modeling matrix

Model	Energy Use Intensity	Control
Full-Size Grocery	Average	Basic
		Advanced
Small Grocery	Average	Basic
	High	
	Average	Advanced
	High	

Results

Full-Size Grocery Store

Informal interviews. Partnerships between the U.S. Department of Energy (DOE), NREL, and large grocery store chains have demonstrated that large businesses are willing to test DR with HVAC and refrigeration technologies. Some national chains have already begun utilizing short-duration DR strategies. Similarly, national grocery and food service chains with small buildings have achieved energy and cost savings through DR tools (DOE 2024a; DOE 2024b).

Quantitative results. Figure shows the time series data of building power consumption for the hottest and coldest days. The baseline and basic control had the same power consumption before the DR event. However, the basic control had a large rebound after the event. The advanced control used more power before the event (pre-cooling/pre-heating) but reduced rebound issues.

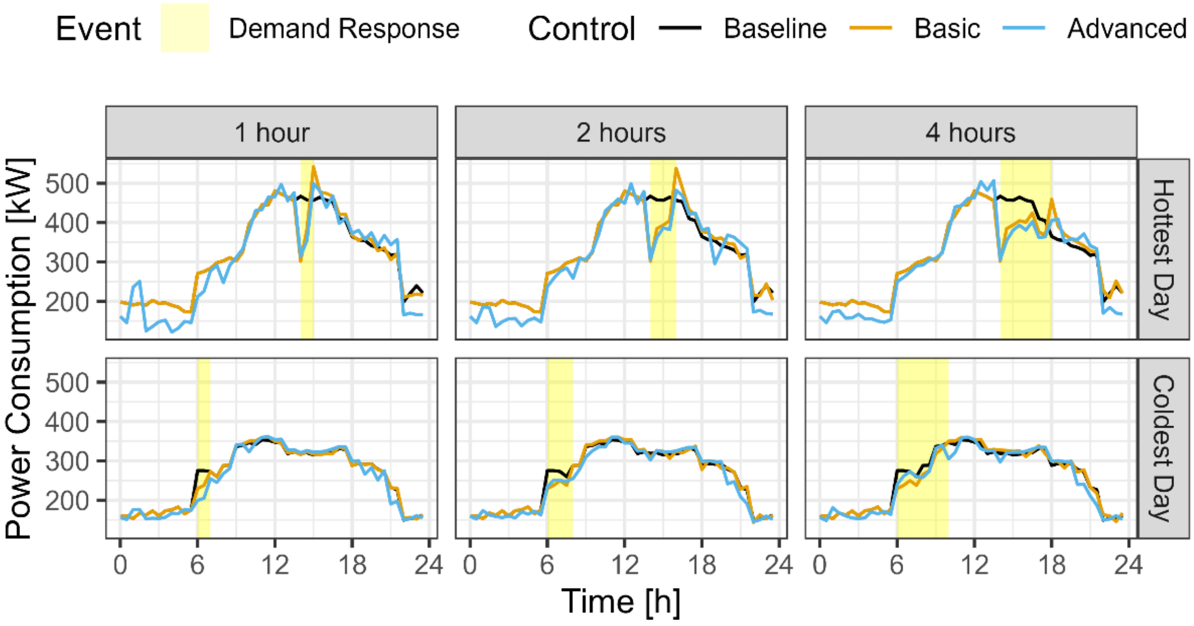

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Figure 1: Example of basic and advanced demand response for full-size grocery store.

Winter demand response. In the winter, refrigeration was the only controllable electrical load. With over 21 controllable refrigerated cases, 10%–20% of cases were in defrost at any given time of day, which further reduced the DR potential. Figure 2 plots the winter demand response event and the average refrigeration error from the target temperature. Also added to Figure 2 is the percentage of cases in defrost. Even when some of the cases were out of defrost, the baseline refrigeration setpoint was above the target temperature for most of the day, indicating the defrost events had a long-term effect on product temperature. The advanced control reduced product temperature in preparation for the DR event, but without the ability to leverage HVAC, DR potential was far lower for the winter event.

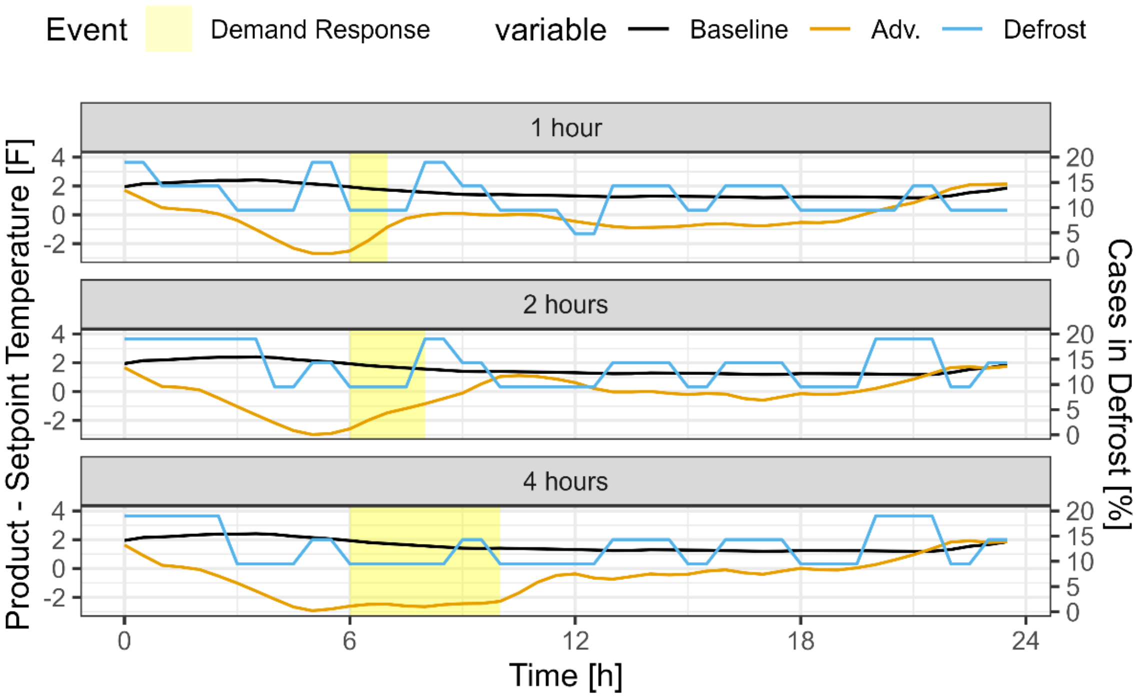

Figure 2: Average product temperature error for the full-size grocery store for the winter demand response event.

Sequential demand response events. For the two sequential days we selected, Figure 3 shows both DR events over a 48-hour period. While the advanced control shifted power consumption for the second day, it was not as significant as the first day. Because the thermal inertia of the building and refrigerated product is a finite resource, there is a limit to how much it can be leveraged. This is demonstrated by the HVAC and refrigeration error from setpoint. If the events grew closer together, the zone temperature or product temperature likely would not be able to recover for the second event.

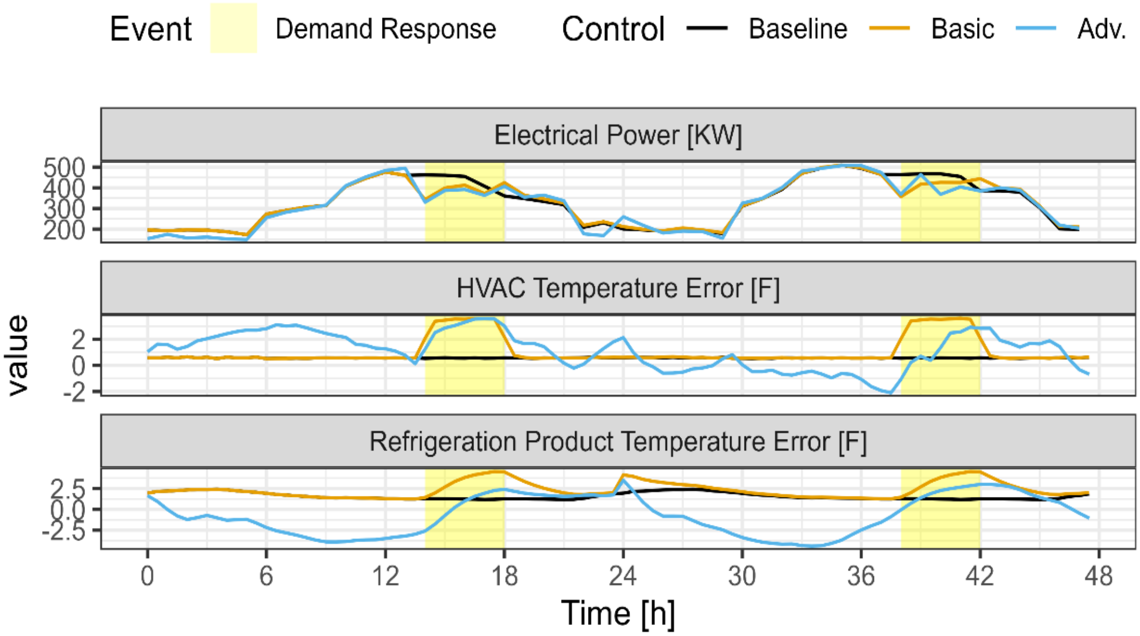

Figure 3. Two sequential 4-hour demand response events for the large grocery store.

Small Grocery Stores

Informal interviews. Anecdotal feedback from our CBO interviewees provided context for the high stakes of maintaining consistent refrigeration temperatures throughout DR events. When grocery stores experience utility outages or refrigeration equipment failures, the extensive financial implications may include both the cost of lost food products (which insurance may or may not cover) and the labor cost required to save perishables (Hawthorn 2024).

Results for small grocery model. Figure 4 displays the power consumption profile for the hottest and coldest days for the small grocery store. The small grocery store peak for the hottest day was roughly 50 times lower than the full-size grocery store. In terms of absolute load shifting potential, the smaller models had less power and fewer assets to leverage.

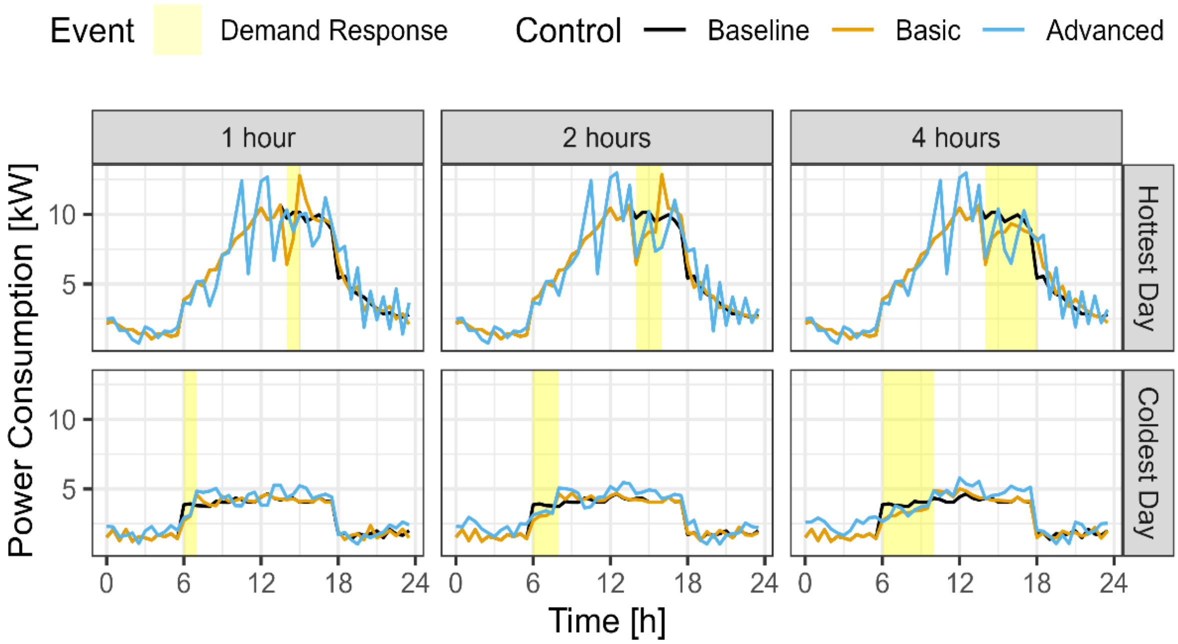

Figure 4. Example of basic and advanced demand response for a small grocery store.

Results for high-energy small grocery model. As discussed in the Methodology section, the high-energy small grocery store model incorporates increased refrigeration energy consumption (switching to open cases, adding more energy-intense lighting, etc.). Likely many other permutations could be set up for small grocery stores, but quantitative data is very limited. These results show the potential trade-offs with only refrigeration changes; however, high-energy small grocery stores might have less efficient HVAC, lighting, plug loads, insulation, and many additional factors. Figure 5 illustrates the load profile for the high-energy grocery store, showing that peak power increased 20% higher than the “efficient” small grocery store.

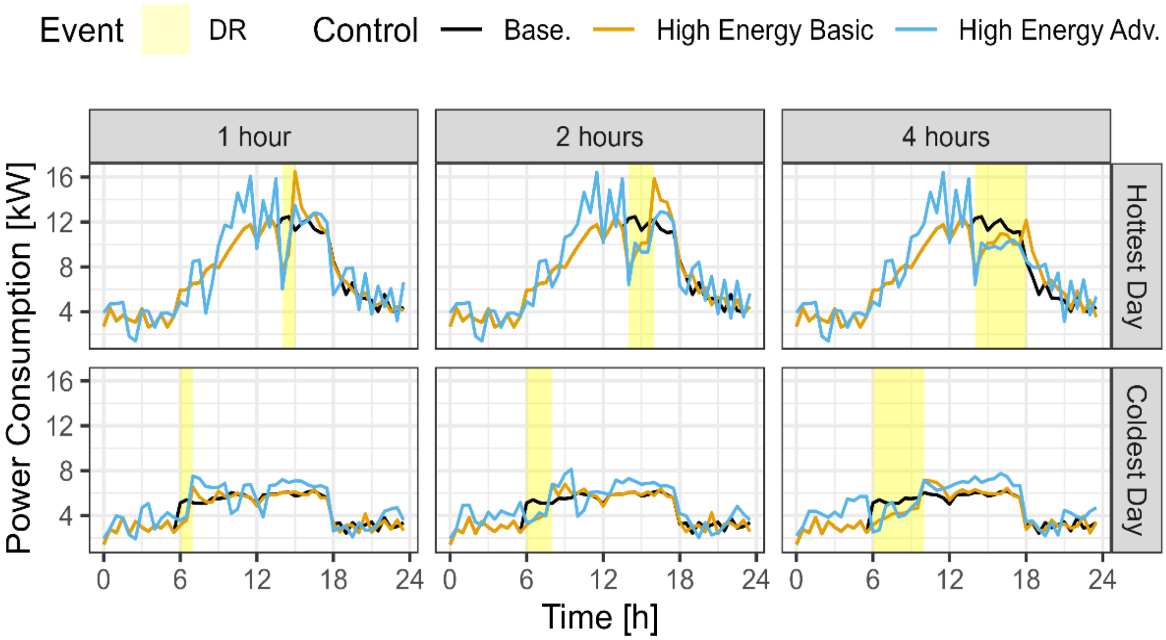

Figure 5. Load profile for the high-energy small grocery store.

Full-Size Compared with Small Grocery Models

Figure 6 shows the DR potential for the models normalized by square footage. Grocery stores of either size benefited from shorter duration DR events regardless of control strategy. In addition, the full-size grocery had more DR potential even when normalized by square footage. Finally, the winter DR potential was lower because HVAC was no longer an asset that could be leveraged to reduce electrical power consumption. Table 2 provides the numerical summary results shown in Figure 6.

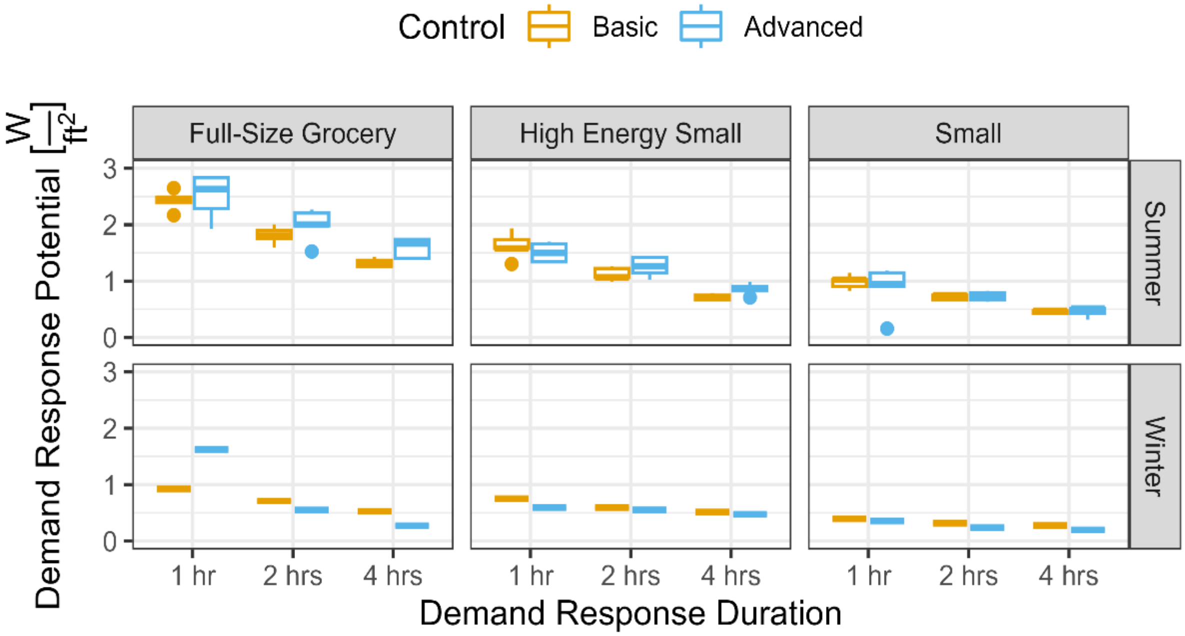

Figure 6. Comparison of demand response potential for the full-size and small grocery store.

Table 2. Average demand response potential for the full-size and small grocery store (W/ft^2)

	Full-size Grocery (W/ft^2)						High-Energy Small Grocery (W/ft^2)						Small Grocery (W/ft^2)					
Season	Summer			Winter			Summer			Winter			Summer			Winter		
Duration of DR	1h	2h	4h	1h	2h	4h	1h	2h	4h	1h	2h	4h	1h	2h	4h	1h	2h	4h
Basic	2.4	1.8	1.3	0.9	0.7	0.5	1.6	1.1	0.7	0.8	0.6	0.5	1.1	0.8	0.5	0.4	0.3	0.3
Adv.	2.5	2	1.6	1.6	0.6	0.3	1.5	1.3	0.9	0.6	0.6	0.5	0.9	0.8	0.5	0.4	0.3	0.2

Figure 7 shows the impact on refrigerated product temperature. As in the field, cases were controlled to manage internal air temperature; however, most grocers are focused on product core temperature. Accordingly, Figure 7 shows the error of the target product temperature versus the average product temperature. Even the baseline shows product temperature variation because defrost impacts were included in the model. The maximum error for refrigerated product was also plotted in Figure 7 to show where product temperature grew too high. For most DR events in the full-size model, basic control allowed product temperature to rise more than advanced control. Due to this issue, grocery stores may hesitate to leverage refrigeration with only basic control as a DR asset, given the considerable risk in raising product temperatures. Advanced control reduced the average product temperature below the baseline values and maintained error below 3°F for all scenarios.

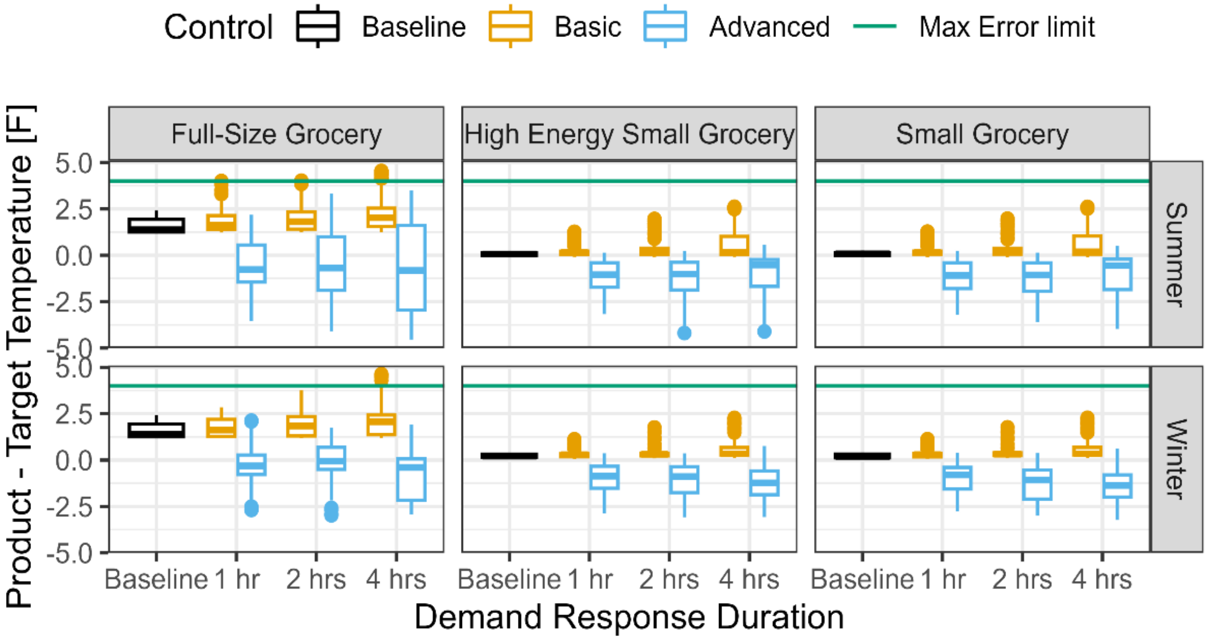

Figure 7. Refrigerant product temperature error for the different grocery store models.

Zone heating and cooling setpoints were expanded from 71°F and 73°F for the baseline to 68°F and 76°F for basic and advanced control. As both basic and advanced control were able to maintain zone temperature for all scenarios, HVAC error was not plotted in the paper.

Figure 8 shows the daily electric energy changes for the models. The purpose of this study was to maximize DR potential, so energy savings and peak demand were not optimized; however, the trade-off between DR, energy consumption, and peak demand is important to understand. Figure 8 shows that the basic control barely affected electric energy, whereas the advanced control changed energy consumption by as much as 15%. This is because the advanced control attempted to save energy as a second priority and also tried to pre-cool or pre-heat in order to improve DR potential. While the advanced control saved energy for the full-size grocery store, it increased energy consumption for both small grocery store models. One potential explanation is that the advanced control had more assets for the full-size store and thus could coordinate them better. The highest increase in energy consumption was for the high-energy small grocery store, likely due to the larger refrigeration capacity.

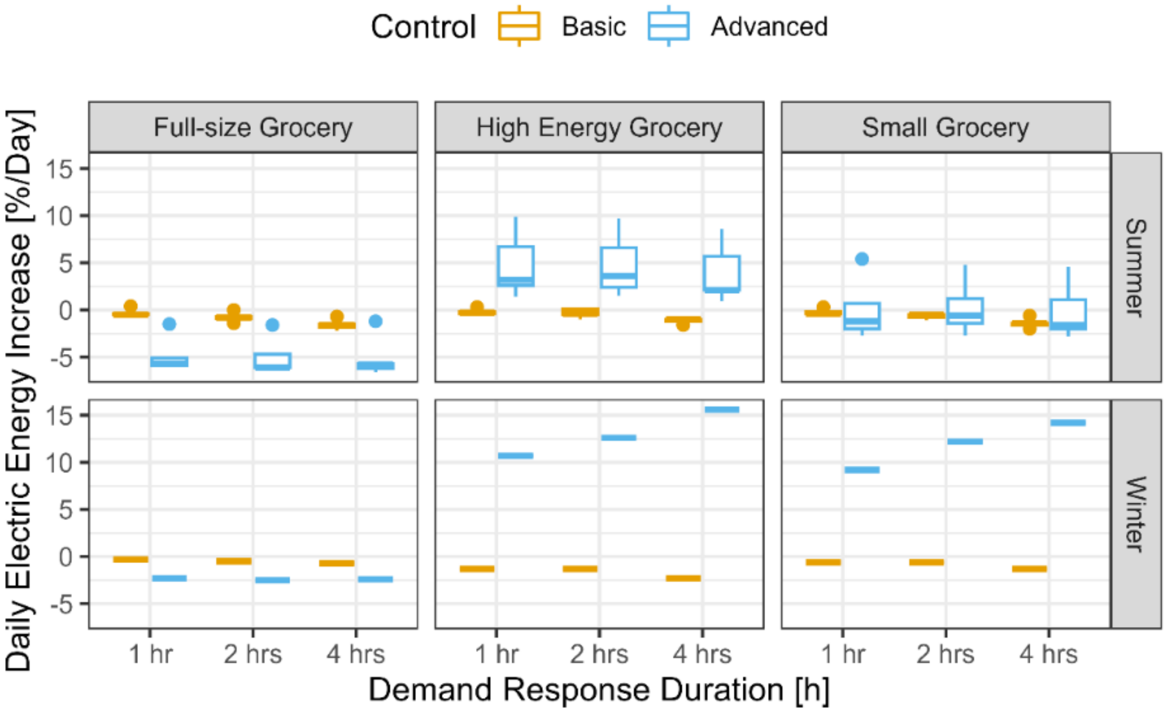

Figure 8. Daily electric energy increase due to demand response event disruptions.

Figure 9 shows the daily peak power increase based on 15-minute time intervals. The full-size grocery had the smallest increase in peak power. The small grocery saw 10%–40% increases in daily peak power. Rebound was the primary issue for basic control, while preparation for the DR event was the main challenge for advanced control. This illustrates the need to balance DR potential with daily peak power, especially for utility tariffs with high peak demand charges.

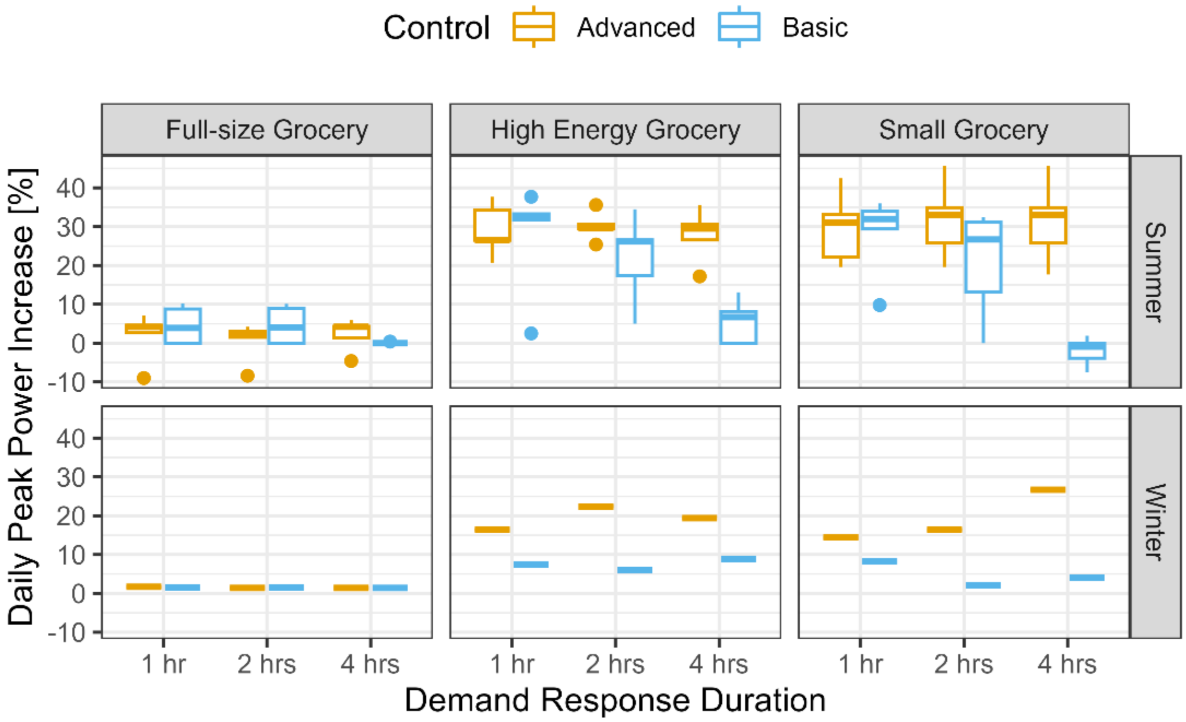

Figure 9. Daily 15-minute peak power increase due to demand response preparation and response.

Conclusions

Comparing Models

These results demonstrate that both large and small grocers can provide demand response potential with basic or advanced control. For instance, the DR performance metrics displayed in Table 2 range from 0.8 W/ft^2 to 2 W/ft^2 for 2-hour summer events. In comparison, a past study on the DR load shed performance of large retail buildings using only HVAC and lighting showed results ranging from -0.2 W/ft2 to 1.0 W/ft2 for 2-hour events (Liu et al. 2023).

In particular, advanced controls demonstrate DR potential during summer months. Winter electric DR potential for the full-size grocery was not large given that our models used natural gas for heating to reflect the prevailing trend in commercial buildings, especially in colder climates. As electrification continues, grocery stores may improve winter DR potential.

The project selected a maximum DR duration of 4 hours, as both control strategies leveraged the thermal inertia of the building and refrigerated product to shift energy consumption. While utilities are asking for buildings to reduce load for up to 12 hours, shorter duration load reductions are better suited for grocery stores, as demonstrated by our results. Shorter events of 2 hours or less allow grocery stores to potentially leverage refrigeration with basic controls; however, advanced control provides better maintenance of product temperature.

Small Grocery Models

Feedback from the interviewed CBOs suggested that small grocery stores might benefit extensively from usage of DR controls; however, our results show that high-energy small grocery stores, the store type most likely to represent small businesses, benefit least from DR. Advanced controls were more successful than basic controls when it came to ensuring refrigeration temperatures did not rise, but advanced controls are frequently out of reach for small grocers. To make DR accessible for small business grocery stores, the stores need energy-efficient equipment, regular maintenance, and best practices. Low-cost, simple solutions are most helpful to these organizations, such as timers or smaller automation systems. Given these organizations' limited staffing, DR should ideally be scheduled/automated so that employees do not need to implement it manually (Oliker and Otero 2024).

While energy costs are an ongoing concern for small business grocers, DR is only important insofar as it can support reduction of their bills without requiring upfront expenditures. Programs that incentivize the purchase of energy-efficient equipment are often reimbursement-based, which presents challenges for organizations without extra operating funds. In addition, small businesses often rent space in a larger building, giving them less control over their space's energy strategy (Oliker and Otero 2024).

Discussion and Next Steps

This project suggests a number of future activities that might benefit DR potential in grocery stores of all sizes. One area of opportunity is coordinating refrigeration defrost cycles. As HVAC technology increasingly electrifies, the industry should prepare to be able to utilize DR during winter electricity demand peaks.

We also recommend further exploration of the needs of small businesses to be able to implement advanced energy strategies such as DR. One barrier is a lack of examples of how to effectively implement DR strategies (Hawthorne 2024). Future research should focus on creating case studies and toolkits for public dissemination. In addition, small businesses often require not only upfront funding, but also technical assistance (Oliker and Otero 2024). This necessitates building trust with local residents and business owners. Existing research and experience with providing technical assistance to communities, as well as the potential of technology pilots and field validations in DACs, can be leveraged.

Finally, the research field must gather more data on small grocery stores, which would support more detailed modelling. Data on these types of organizations will provide insights for programs that can keep small businesses open and make it possible for small grocery stores to be part of the clean energy transition.

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