

Demand Response Capabilities of Industrial Refrigerated Warehouses: Experiences in Practical Implementation

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ABSTRACT

Storage capacity in certain end uses can be leveraged to enable flexible demand response (DR) that can absorb power generation intermittency. One opportunity is in industrial refrigerated warehouses, used by logistics operations for storing food products as they move from production facilities to consumers. California hosts the largest amount of refrigerated space in the U.S., with refrigeration load of about 23,100 tons of refrigeration (TR) and associated electric power consumption of about 46 MW. The estimated DR potential of refrigerated warehouses is 0.575 kW / TR, corresponding to about 13 MW. The Electric Power Research Institute (EPRI) team investigated the potential of automated DR at an industrial refrigerated warehouse in California. Using OpenADR 2.0b protocols, DR signals could be reliably transmitted from a virtual top node (VTN) to the end use, to increase or decrease the compressor power used by the facility by up to 30% during a DR event. This was done without any adverse consequences on the food products stored in the warehouse. A detailed understanding of heat transfer processes in the warehouse, along with an understanding of the control system, was necessary to obtain the response desired. The team also found floor heating to be another source of demand reduction for the site that can be appropriately tuned to produce the desired response with little or no extra energy cost. Experience indicates that practical implementation of flexibility measures is best achieved by integrating flexibility with existing cost optimization services, whose algorithms often use detailed modeling of the facility to minimize operating costs.

Introduction

Globally, the industrial refrigeration sector is dominated by India, the United States, and China, with 150M m³, 131M m³ and 105M m³ of the collective 616M m³ global warehouse capacity respectively (Salin 2018). Warehouses in the United States are overall larger in size but fewer in number, while warehouses in India are smaller in average size but more numerous. This is significant because larger warehouses, on average, use less energy per unit volume per year, as reported in a survey conducted by the University of California Davis [Singh 2008]. The annual growth rate of consumer spending on grocery retail varies widely across the world, around 2%-4% for a large fraction of developed countries, with a corresponding associated growth rate in logistics infrastructure. In a study prepared by the U.S. Department of Agriculture, there are over 11M m³ of gross refrigerated warehouse space in the state of California alone (USDA 2019). Assuming an average of 2100 TR capacity [7385 kW_{th}] per M m³ (Stoecker 1998) and an average of 1.3 - 2 kW of electric power per ton of refrigeration capacity (0.37 – 0.57 kW_e/kW_{th}), (ASWB 2018) this translates to approximately 36 - 46 MW_e of total refrigeration electric demand for the refrigerated warehouse inventory in California, where this study focuses.

Furthermore, this electric demand represents only a fraction of the total industrial refrigeration load that also includes food and agricultural processors as well as beverage producers (ASWB 2018).

In a study addressing the refrigerated warehouse sector in California (Scott *et al.* 2015), a total DR potential of 22 MW is estimated. The study also provides detail on the type of warehouses that are most suitable for DR support, notably those that have advanced control capabilities. However, changes in consumer behavior, reinforced by the COVID-19 pandemic that began in late 2019, combined with technological changes that allow for more sophisticated control of loads, could see this potential multiplied severalfold (Amarnath *et al.* 2022). A recent study for UN Environment OzonAction (Evans 2018) provides details on individual components of the food chain, providing insight into recent trends in refrigerated warehouse technology, noting that there is significant variation and that efficiency measures could reduce loads substantially. These efficiency measures should be borne in mind when estimating the future of demand flexibility in the refrigerated warehouse sector.

A detailed and comprehensive report written for EPRI (ASWB 2018) provides an overview of the current state of DR potential of refrigerated warehouses in California, considering the emerging needs of the utility sector for flexible loads due to a changing generation mix that relies increasingly upon renewables. The report outlines the variety of grid services that the industrial refrigeration sector could provide. It presents the case for standardizing communications between the grid and the customer via OpenADR2.0b, an open-source information model that can transfer signals bi-directionally, for example, a DR trigger signal from a load aggregator to a customer, or a reporting signal from the customer to the load aggregator to relate the amount of response that actually took place at the site. Figure 1 shows an aerial view of the site where experiments took place.



Figure 1: Aerial view of the 65,000 m² facility that hosted the demonstration discussed in this paper. Refrigerated semi-trailers loading and unloading at the dock are clearly visible. *Source:* Lineage Logistics 2021.

In 2016, the California Energy Commission, under its EPIC Program, awarded funding to EPRI to implement a demonstration of DR capabilities enabled by the combination of a modern and efficient refrigerated warehouse, a sophisticated control system, and the OpenADR

communications protocol. The present paper is a summary of the implementation and outcomes of using OpenADR 2.0b for telemetry and implementation on compressor and floor heating loads.

Experimental Setup

For this research project, the EPRI team partnered with a large logistics services provider, who hosted the demonstration at one of their warehouses, located in one of the logistics hubs in southern California. The plant with a gross floor area of approximately 65,000 m², is in Southern California Edison's (SCE) electric service territory, but is a direct access customer. These type of consumers purchase energy from a competitive provider, rather than from a regulated electric utility. The warehouse is divided into 11 rooms, including freezer rooms (operating at -18°C), cooler rooms (-18°C to 0°C), dry storage area (over 0°C), and dock areas (4°C) where food is briefly stored after being unloaded from the refrigerated trucks before it is placed in the appropriate cold storage room. While the temperature of food items in cooler rooms and dry storage areas must be kept within carefully controlled limits, the vast majority of food stored in the frozen rooms can be over-cooled without damage, thereby allowing the storage of thermal energy. Because of the tolerance for temperature variations, the frozen rooms are used as thermal storage in this study.

The refrigerant used at this plant is ammonia (NH₃). NH₃ is a common refrigerant for industrial refrigeration due to its high-cycle efficiency. The plant is served by a total of nine compressors, which in groups serve the low-, medium-, and high-temperature zones. The average daily load profile at the plant for October-December 2020 is shown in Figure 2. While the compressors are the largest individual loads, there are clearly other loads that also play a major role in the total plant electricity consumption. The ability to leverage these additional loads for DR will be addressed later. The refrigerated warehouse considered in this study was first commissioned in the 1980s and is representative of many similar plants statewide and nationwide. Since the acquisition by its current owners, the plant has recently received several efficiency upgrades, including, notably, variable-speed drives on several of the NH₃ compressor motors. Operation of the plant refrigeration system is provided by proportional-integral-derivative (PID) controllers, which control temperature by adjusting the fan speed of evaporators located in each room to provide varying amounts of heat removal. In turn, the refrigerant temperature at the exit of the evaporator coils is monitored to control the refrigerant flow rate and hence the compressor speed and associated electric power draw. Because of the variable speed control, it is possible to fine-tune the power draw and vary power consumption without cycling compressors on and off. The significance of this, for the purposes of this project, is that adjusting the temperature setpoint of individual rooms is the mechanism by which compressor electrical load can be adjusted to provide DR.

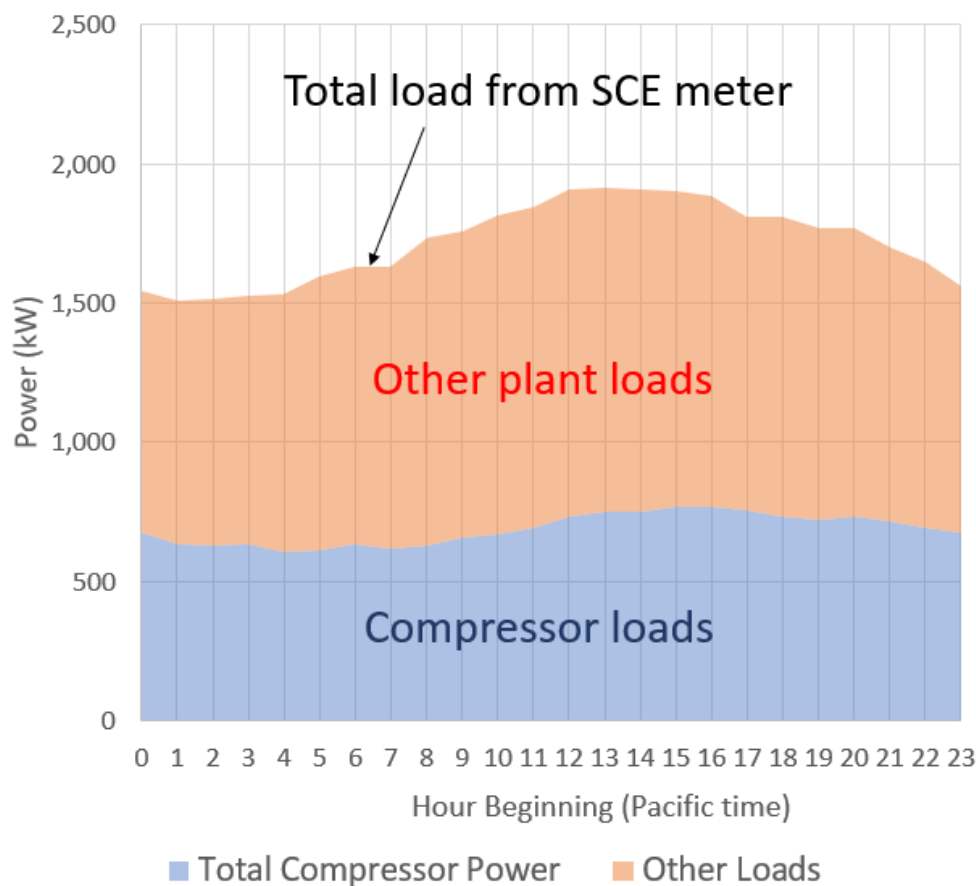


Figure 2: Total and compressor load at the refrigerated warehouse. *Source:* EPRI.

Adjusting temperature setpoints to control power consumption is not a new concept at this plant. The same mechanism is used in a process commonly known as “flywheeling,” whereby compressor power is adjusted in response to hourly, daily, or weekly forecasts of energy unit cost. When energy cost is low, compressor power is increased, and vice-versa. The thermal capacity of the frozen food serves as energy storage. While this mechanism appears simple, adjusting power demand to minimize energy cost while ensuring that food temperature is maintained within limits set by the warehouse customers is a complex optimization process. For the warehouse in this study, optimal scheduling of the temperature setpoints is provided by a third-party service that specializes in refrigerated warehouse energy system optimization. Specifically, the optimization process adjusts the temperature setpoints to reduce the temperature in the frozen rooms when electricity is less expensive, so that when electricity cost is high the compressors can operate at lower capacity, without allowing the food temperature to exceed a defined upper limit. A recent implementation of the flywheeling process resulted in energy cost savings that produced a payback time of only a few years. While flywheeling can be used for optimizing day-to-day operations, DR can be load shifting or shedding for utilities to further reduce grid loads for ancillary services.

The control configuration at the test plant provided an excellent starting point for implementing the DR demonstration. Specifically, to implement DR, it is necessary to adjust the temperature setpoint of one or more rooms – upward to reduce load, and downward to increase load. Moreover, a project requirement was to use the OpenADR 2.0b protocol to communicate

the message to adjust the temperature setpoint, and to monitor the response of the plant to the DR signal. The high-level architecture of the refrigeration plant DR reflects the need for the framework to be broadly applicable. For example, it should be able to use legacy system energy management and/or optimization services that may not be able to receive or send OpenADR communications, and different intermediary OpenADR-enabled virtual end nodes that translate OpenADR into a data stream that can be used by the legacy system. The high-level architecture, including the Virtual Top Node (VTN) and intermediary Virtual End Node (VEN) is shown in Figure 3.

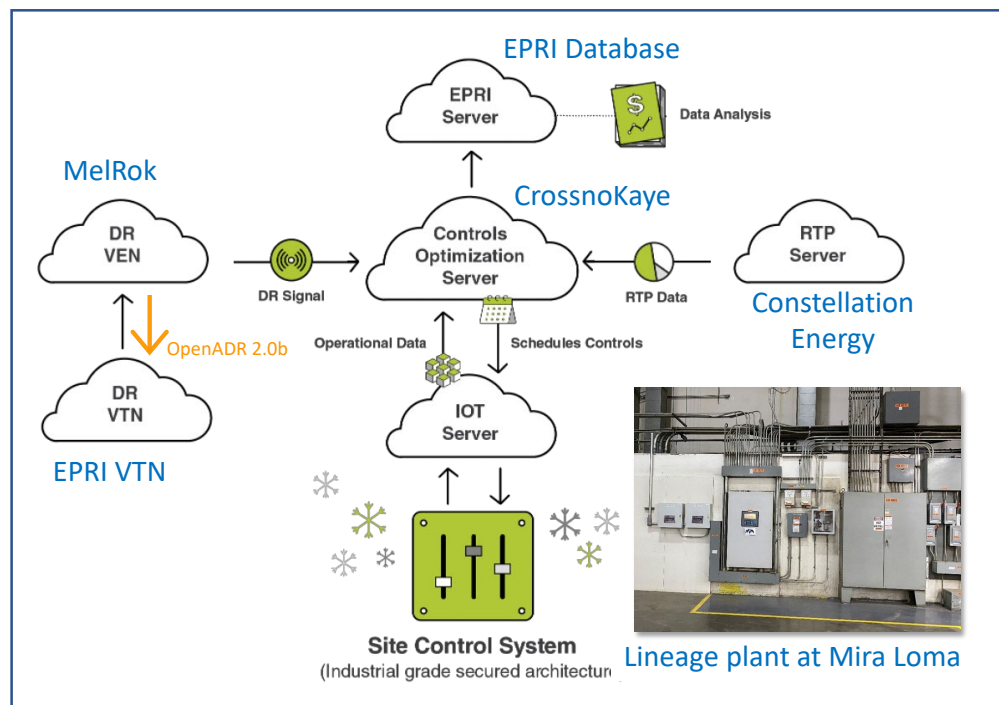


Figure 3: Architecture to deliver a DR signal from a Virtual Top Node to the end-use, via an OpenADR 2.0b intermediary Virtual End Node. *Source:* EPRI.

The architecture leverages new capability in the OpenADR 2.0b protocol and uses an intermediary to translate OpenADR 2.0b messages to the scheduling optimization system, which is not configured to receive or send OpenADR communications. The use of the intermediary VEN gives the architecture a high degree of flexibility by allowing legacy systems to interact with the outside world via OpenADR 2.0b. In turn, OpenADR 2.0b is of interest to the electric utility industry because it allows standardization (and thus, higher adoption) while allowing higher flexibility in relaying information (e.g., by enabling direct reporting of the outcomes of a DR signal). Using this architecture, EPRI (acting as a grid operator or aggregator) uses a VTN to issue a DR notification, which includes information on the power level requested and duration via an OpenADR 2.0b message. The message is received by the VEN, and its contents are relayed to the optimization service via a custom Control API. The Control API uses the received information to produce a temperature setpoint schedule and delivers this schedule to the plant controls via an internet-of-things (IoT) server. Submetering information at the plant is accessed by the Control API and sent to the VEN. The VEN interprets the information and reports this to

the VTN at regular intervals via OpenADR 2.0b, providing feedback on the response to DR signals to the virtual aggregator or grid system operator.

DR signals from the EPRI virtual top node (VTN) go to the MelRok Touch Gateway. The sequence of events that takes place to respond to a DR signal is as follows:

1. Event behavior configuration occurs in the MelRok cloud (portal).
2. EPRI hosts the DR Automation Server (DRAS).
3. The automated DR (ADR) event is setup and configured on the DRAS. (Previously, the DRAS installed a matching certificate to allow communication with the Touch gateway.)
4. The CrossnoKaye system optimization service hosts a restful service to allow the Touch Gateway to receive the DR signal.
5. When the event is configured on the DRAS, the Touch Gateway downloads and configures the event schedule.
6. When the event is scheduled to start:
 - a. The Touch Gateway calls the application programming interface (API) to notify the CrossnoKaye service that the event has started.
 - b. The Touch Gateway triggers the agreed-upon sequence of operations.
7. During the event:
 - a. The Touch Gateway calls the API to obtain operational data from the CrossnoKaye service.
 - b. The Touch Gateway relays information to the EPRI DRAS via OpenADR 2.0b using the pre-determined data structure.
8. When the event is finished:
 - a. The Touch Gateway triggers the agreed-upon sequence of operations to return to the initial state.
 - b. The Touch Gateway calls the API to notify the CrossnoKaye service that the event has been completed.

OpenADR 2.0b protocol was tested extensively throughout the pilot study. The power timeseries data that was received by the VTN matched the metered data without any significant error. Throughout the pilot study, 18 experiments were run on separate days at varying times and durations varying from 30 minutes to 24 hours in the afternoon. The results of the research showed 100% of the signals being successfully sent and received through OpenADR 2.0b, proving a reliable method of telemetry.

Insights From Modeling

To obtain a better understanding of the dynamics of temperature vs. chiller operation in the warehouse frozen rooms, the team constructed a qualitative numerical model that captures the essential heat transfer processes based on the following system variables: the heat transfer $\dot{Q}_{evap}$ from the air to the refrigerant inside the evaporator (at temperatures T_{air} and T_{sat} respectively), which has surface area A_{evap} ; the heat transfer $\dot{Q}_{food}$ from the food to the air (at average food temperature T_{food}); the heat transfer from the warehouse floor to the air, $\dot{Q}_{floor}$; the heat transfer from the warehouse walls to the air, $\dot{Q}_{walls}$. These variables are coupled by a

series of simple heat transfer relations, that can be derived readily. The key relations in this model are:

$$\dot{Q}_{evap} = h_{evap} A_{evap} (T_{air} - T_{sat}) \quad 1$$

$$\dot{Q}_{food} = h_{food} A_{food} (T_{food} - T_{air}) \quad 2$$

and similar relations for $\dot{Q}_{floor}$ and $\dot{Q}_{walls}$. The saturation temperature of the refrigerant, the outdoor ambient temperature, and the temperature of the subfloor are assumed known (based on reasonable engineering assumptions, with values of -29.44°C, 30°C and 1°C respectively), with all other variables calculated. More details on the model and assumptions can be found in the report on the project to the California Energy Commission (Amarnath et al. 2015). Such equations reveal how the evaporator transfers heat from the air thereby changing its temperature. Similarly, the temperature of the food, which has a thermal capacity that is orders of magnitude larger than that of the air, can only be changed by the surrounding air at a different temperature. Control of the rate of heat exchange is via the convection coefficient at the evaporator, that can be modeled as:

$$h_{evap}(t) = K_p + K_i \int_0^t \epsilon(\tau) d\tau \quad 3$$

This is simply a proportional-integral-derivative (PID) controller with zero derivative term, where K_p is the proportional constant, K_i is the integral constant and $\epsilon(\tau)$ is the tracking error. Values of these were chosen so that the model behavior matched observed experimental behavior. By deriving ancillary heat transfer relations and obtaining information from the plant operators concerning parameters such as mass of food, total fin area of the evaporator (A_{evap}), dimensions of the room, controller constants that produce response similar to the experiments, etc., the team obtained the numerical solution for a heat transfer process that included an initial setpoint temperature drop at 0 hours, followed by a return to default conditions at 10 hours. Figures 5 and 6 show temporal evolutions of frozen room temperatures.

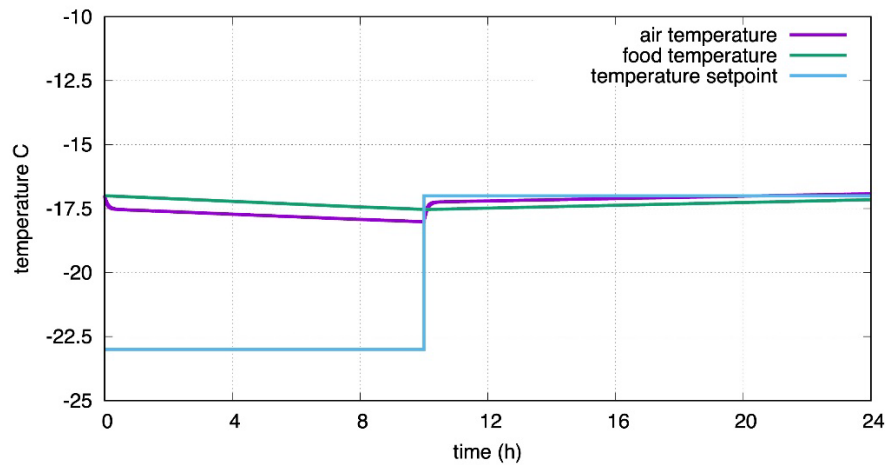


Figure 4: Temporal evolution of frozen room temperatures prior to and following a room setpoint reset. *Source:* EPRI

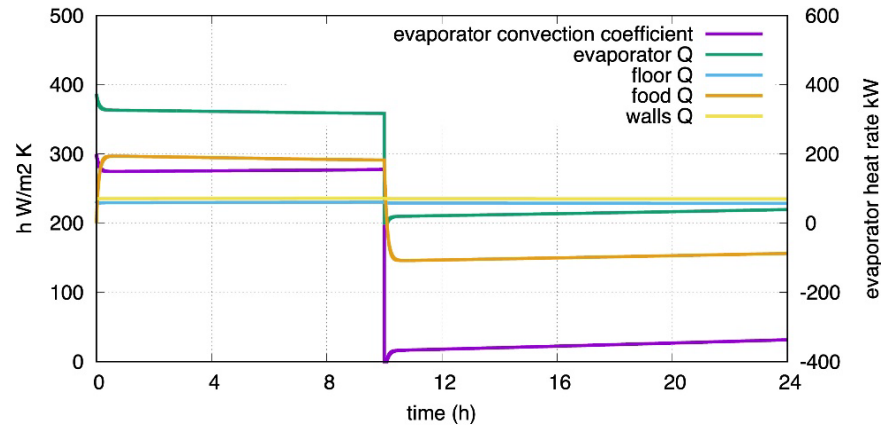


Figure 5: Temporal evolution of evaporator convection coefficient (h – left axis scale) the heat transfer rates (Q – right axis scale) between frozen room components prior to and following a room setpoint reset. *Source*: EPRI.

As shown in Figure 5, from equilibrium initial conditions at -17°C , the temperature setpoint is reset to -23°C for the first 10 hours, then returned to -17°C for the remainder of the time. The temperature of the air drops rapidly for a short time, approximately $\frac{1}{2}$ hour, then follows a slow, essentially linear decline. The temperature of the food, on the other hand, declines linearly for the entire time, following the same rate as the long-term decline of the air temperature. When the setpoint is returned to its original value of -17°C at hour 10, the air temperature quickly regains several degrees, almost returning to the initial condition, and then begins a linear slow increase. The food temperature inverts its linear decline and begins a slow linear increase.

The explanation for this interesting behavior can be found by considering the evolution of the individual heat transfer processes, $\dot{Q}_{evap}$, $\dot{Q}_{food}$, $\dot{Q}_{floor}$ and $\dot{Q}_{walls}$, shown in Figure 6. $\dot{Q}_{evap}$ begins at around 375kW, then rapidly and exponentially declines to a 326kW steady-state. This is primarily a result of the PID control, whose proportional component is reduced as a consequence of the reduced tracking error, while the integral component increases slowly. At the same time, the food starts to transfer heat to the air as the temperature of the air drops, giving rise to the characteristic slow quasi-linear decline. The floor and wall heat transfer rates do not change appreciably, remaining at around 60-70 kW. It should be noted that the quasi-linear regime is associated with a constant heat flux regime resulting from the interaction of the PID control with the physical system parameters. The PID sets the evaporator fan speed, and the temperature of the air then responds so that the heat extracted from the air by the evaporator coil balances all other heat sources or sinks (food, walls, roof, floor). It should further be noted that the evaporator can only remove heat (so response to setpoint changes is asymmetric), and that air temperature has a lower bound, that of the refrigerant saturation temperature, but that this lower bound cannot be reached with finite fan capacity or evaporator surface area.

When the setpoint is reset to its original value of -17°C , at hour 10, the heat flow from the evaporator stops for a short time, while floor and wall heat flows quickly result in an increase of air temperature. After the air becomes warmer than the food temperature, there is a net transfer of heat from the air to the food. As the tracking error reverses sign and becomes much smaller in magnitude, the integral component of the controller becomes dominant and the fans turn on

again, at a low capacity, so that the evaporator continues to absorb heat from the air even though the air temperature is slightly lower than the setpoint.

The model revealed important features of the complex heat transfer process dynamics between the evaporators, the freezer room surfaces, the floor heaters, and the food, as follows:

1. The heat transfer process (cooling of the air mass) occurs relatively rapidly, with a time constant on the order of one hour.
2. Once a large enough temperature difference is established (several degrees), effective heat transfer can be established between the air and the food.
3. There are many factors that may lower the rate of temperature change even when room evaporators operate at near maximum capacity: opening of doors to other rooms, forklift movement/heat, human temperature gains, high thermal mass of the food (each frozen room contains several thousand tons of food), , also because of the limited ability of surfaces to exchange heat with air.
4. The system controller tracks the air temperature, not the food temperature, although the heat content is primarily in the food. Consequently, changes in food temperature always lag changes in air temperature.
5. The heat produced by the floor heaters, which eventually ends up in the freezer room space, is likely a significant contributor to the heat balance in the room comparable to the wall heat.
6. Control parameters that are set in the PID control can affect the dynamics of the system, particularly the speed of the compressor, and the activity of the compressor following a temperature reset. Care should be taken in determining the setpoint, because the time integral of the tracking error can lead to unexpected consequences.

The model assumptions were verified with the use of infrared imaging in the refrigerated warehouse that was the object of this study. Moreover, additional components that could be considered in the model were also identified. Figure 7 shows heat sources and sinks inside a frozen room.

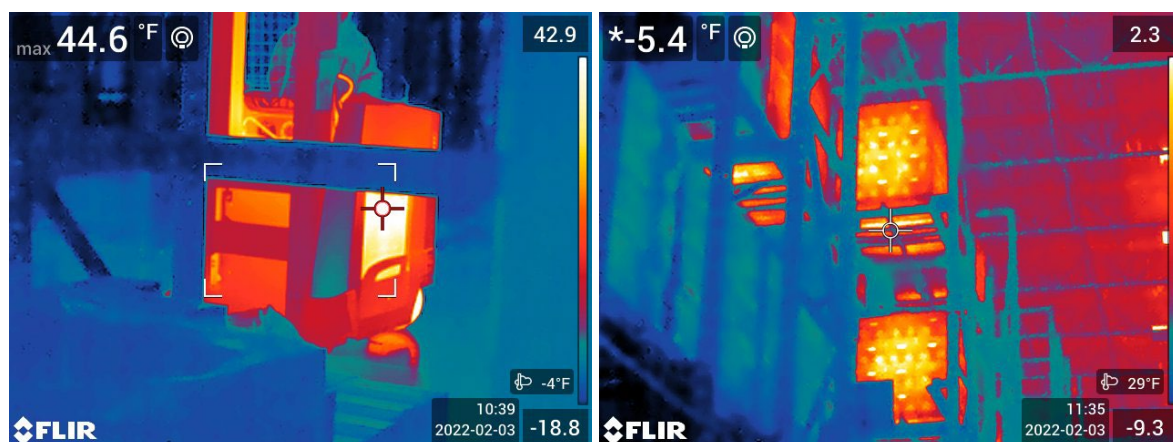


Figure 6: Examples of heat sources and sinks inside a frozen room: an electric forklift (Left), food pallets and perimeter ceiling (Right). *Source:* EPRI.

Ceiling, floor and wall temperatures were consistent with the model assumptions. The team also noticed that the throughput of food pallets, and the electric forklift trucks that carry them, could be an additional source of heat to consider in the model. Generally, forklift trucks and the food pallets they carry could be several degrees or even tens of degrees hotter than the room setpoint. Modeling these would require access to statistics on the temperature distribution of incoming food pallets, as well as of the path of the forklifts. Such statistics are increasingly available at warehouses as a function of local logistics optimization.

Experimental results

Compressor Loads

EPRI conducted several DR tests in 2020 and 2021, that provided the basis for the modeling effort. Based on the modeling insight, the EPRI team triggered further DR events, one of which occurred on the weekend of September 25-26, 2021. This experiment was intended to measure the power response to an initial reduction of temperature setpoint (power consumption should increase), followed by an increase in temperature setpoint (power consumption should decrease). During the weekend, the transfer of food in and out of the frozen rooms is minimal, reducing experimental “noise.” As an additional measure to reduce noise, the defrost process for the frozen rooms was de-activated during the DR event. The temperature setpoint (-18°C [-1°F] during normal operation and -23°C [-10°F] during DR event) and room temperature response, for room 8, one of the frozen rooms, is shown in Figure 8.

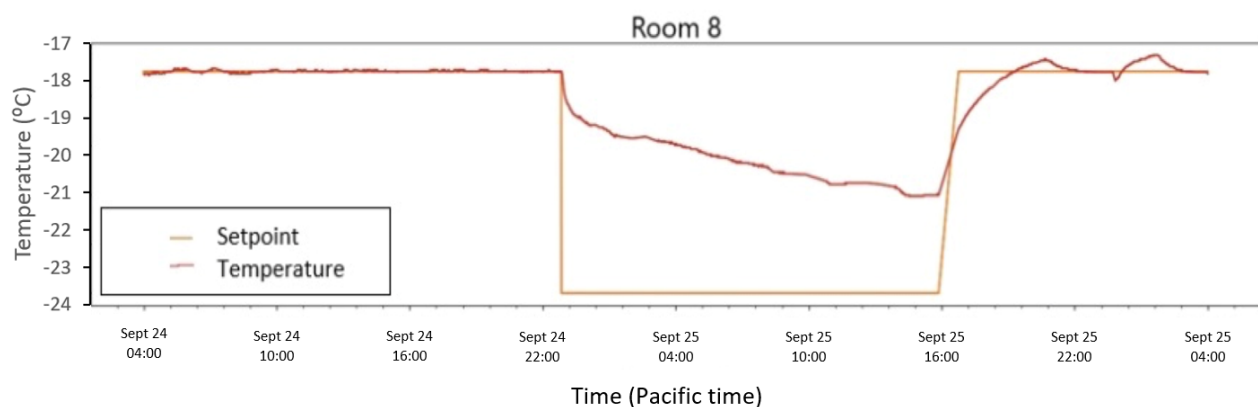


Figure 7: evolution of air temperature in one of the frozen rooms following setpoint resets. *Source:* CrossnoKaye.

The temperature response of room 8 was very close to the analytical model. Prior to the pre-cooling event, the air temperature tracked the setpoint very closely for at least 18 hours. At the onset of pre-cooling, the expected exponential decline of air temperature, lasting less than one hour, was observed, followed by the quasi-linear decline in temperature associated with heat removal from the food. At the end of the pre-cool period, the air temperature climbed exponentially, driven by floor heating, heat transfer from the perimeter walls and roof, introduction of food pallets, forklifts, and defrost cycles.

The corresponding whole-plant power response is shown in Figure 9. Noting that the time is in pacific time, the pre-cool period begins at 12 a.m. on September 25, and lasts until 5 p.m. on the same day. The baseline average power draw from all the compressors before the pre-cooling

period is 1038 kW. During pre-cooling, the average power draw increases to 1310 kW, 26% higher than baseline. In the power-down period, following the pre-cooling, power draw drops to 721 kW, a 30% reduction compared to baseline, and is sustained for a period of the same length as the pre-cooling period, from 5 p.m. on September 25 to noon on the following day. After the DR period, power draw slowly returns to baseline levels. The slow return to baseline is a natural consequence of the fact that there are no temperature setpoint resets.

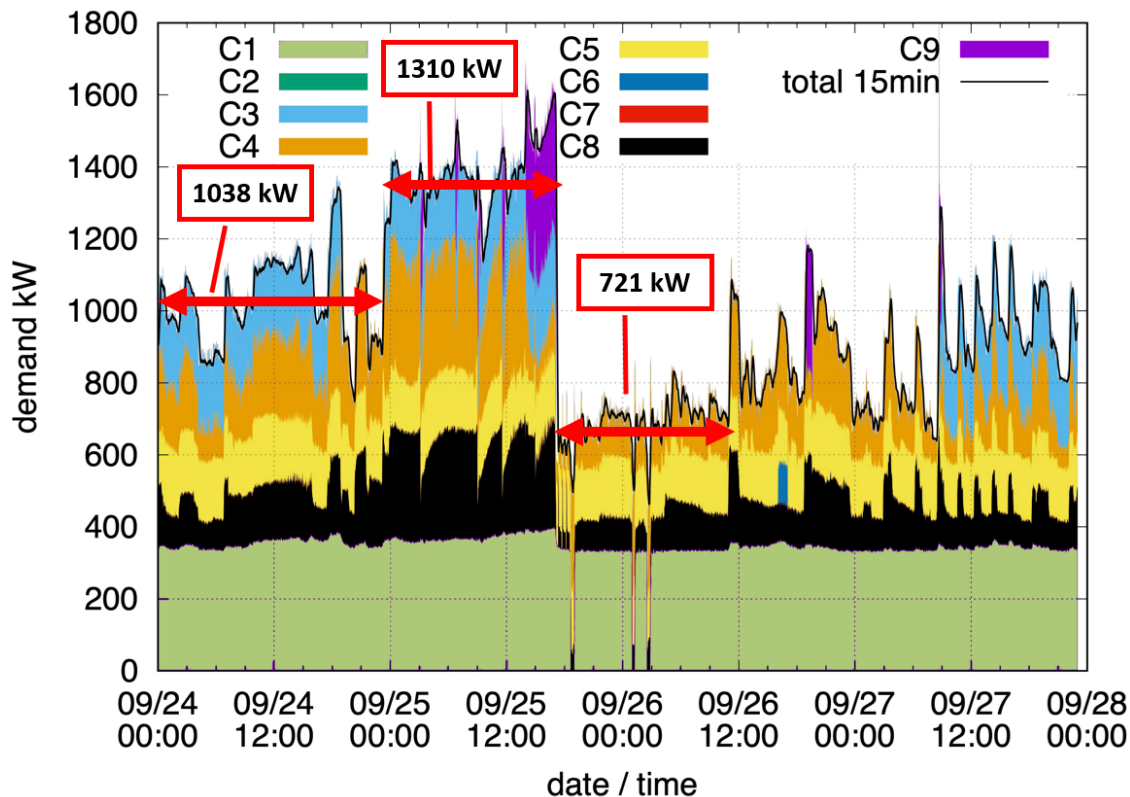


Figure 8: Overall compressor response to the temperature resets in the September 25-26, 2021 experiments. Compressors 3, 8 and 9 are associated with the low-temperature circuit and display the most response. Note that the time zone is pacific time. *Source: EPRI.*

While the DR setpoint schedule was the same for all rooms, the response was not uniform, due to different room configurations, food storage situations, and prior defrosting events. The response of Room 8 was closest to the analytical model. In Room 8, prior to the pre-cooling event, the air temperature tracked the setpoint very closely for at least 18 hours. At the onset of pre-cooling, the expected exponential decline of air temperature, lasting less than one hour, was observed, followed by the quasi-linear decline in temperature associated with heat removal from the food. At the end of the pre-cool period, the air temperature climbed exponentially, driven by floor heating, heat transfer from the perimeter walls and roof, introduction of food pallets, forklifts, and defrost cycles.

Other Loads

In addition to the compressor loads, the team identified additional electrical loads that are compatible with DR. These are electric floor heaters, and forklift truck chargers. The floor

heaters prevent the ground and foundation of the building from freezing and cracking. While water/glycol floor heaters, using heat recovered from condenser, are used in some newer facilities, at this test site all the floor heaters were electric resistance, with combined rated power of 700 kW. The heaters for this plant are either in the “on” state, or in the “off” state, controlled by a simple deadband controller. Nine of the eleven rooms are fitted with floor heaters, but monitoring and automated control is only available in three out of the nine rooms. The team first characterized the operation of the monitored floor heaters by observing their power consumption over the course of one week.

The result of this is shown in Figure 10. While there is variation, the total heater power on most days is tightly clustered around an average power consumption of approximately 130 kW for the rooms in question, corresponding to approximately 390 kW extrapolated to the entire plant. To test the DR capability of the floor heaters, the team changed the setpoint of the controllable floor heaters from the default value of 1°C to -18°C, corresponding to the setpoint of the frozen rooms for a two-hour period. With this setpoint reset, it was expected that all heaters would move to the “off” state independently of their prior state. The team conducted a 2-hour-long DR experiment, beginning at 5PM and ending at 7PM. The results of the DR experiment, shown in Figure 11 confirm the expectation that all heaters would turn off for the duration of the experiment. Furthermore, this DR action had no measurable effect on the floor temperature due to the large thermal mass of the floor and short DR duration. Because the heaters are simple resistances, their response is immediate, and they can be used in conjunction with the compressor DR to improve speed and flexibility, producing fast and flexible DR. Forklift chargers are also another potential DR resource; however, this is more difficult to implement because it requires the presence of a forklift charging optimization system to prevent interference with plant operations. The implementation of such a system is currently being considered.

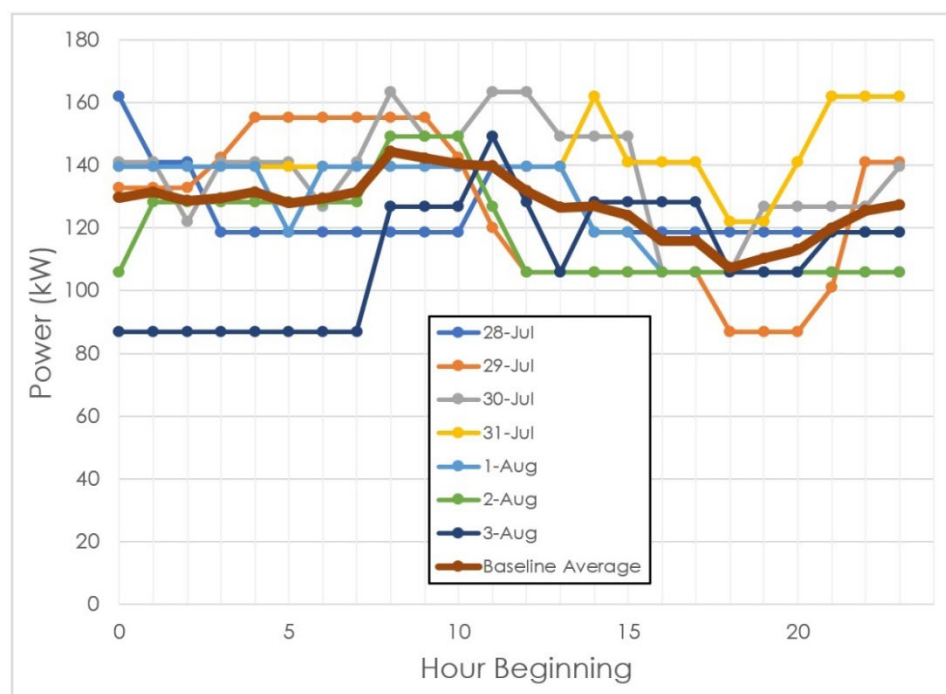


Figure 9: Experiments to characterize DR potential of floor heaters - Daily and average combined power draw of floor heaters for three rooms over the course of a week. *Source: EPRI.*

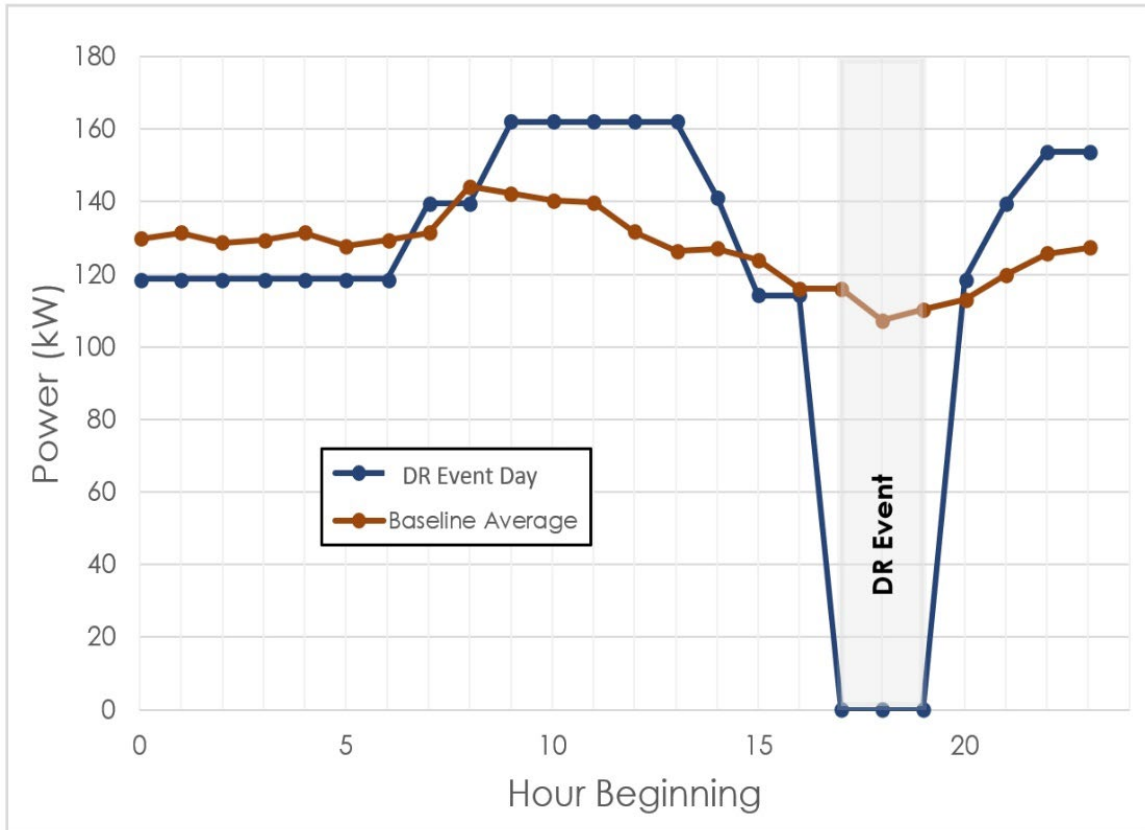


Figure 10: Experiments to characterize DR potential of floor heaters - Floor heater power draw on day of DR event, showing that floor heater power is reduced to zero during the 17:00 to 19:00 DR event. *Source: EPRI.*

Discussion And Conclusions

The main conclusion that can be drawn from this work is that by carefully controlling the temperature setpoints correctly and by setting times that allow the food temperature to decrease, a symmetric power-up (pre-cool) and power-down ratio can be attained from the refrigeration compressors. This enables recovery of energy used to pre-cool the food prior to power-up. This also means that the reduction in power draw during power-down is essentially the same as the increase in power during power-up. This finding is essential because it means that round-trip efficiency is high, and that industrial refrigeration compressors are an excellent DR resource.

A secondary and important conclusion can also be drawn. The necessity to pre-cool the food prior to a power-down event complicates planning and thus reduces flexibility. This requirement could be eliminated by making the default setpoint a few degrees lower than the current practice (in this case, -18°C [0°F]). This, in turn, would produce a small reduction in efficiency for the plant as a whole. On the other hand, the added flexibility may allow increased renewables on the grid and thus overall lower emissions. Similarly, higher costs from reduced efficiency may be offset by higher revenues from participation in DR markets. There is no universal answer to where the default setpoint should be set for optimal flexibility, optimal economics, or optimal emissions. This is a complex problem that can only be solved by integrating flexibility into the legacy optimization system that currently minimizes plant costs, combined with an electricity cost that reflects emissions.

The project demonstrated the effectiveness of end-to-end, bidirectional, automated communication (using OpenADR2.0b). The project team built the end-to-end communication pathway through a combination of “off-the-shelf” components and some “custom” components, mimicking what would be done in a “real-life” project. The team also validated the applicability of the OpenADR 2.0b specification, wherein a return signal is sent back to the DR server validating a demand increase or demand reduction action taken by the end-use system. The team was able to achieve a 31% decrease in compressor demand during one of the DR events. Finally, the team identified additional loads that are commonly found at refrigeration facilities, such as floor heating and forklift charging, that could also take part in DR with appropriate system integration. Such additional resources complement the traditional refrigeration compressor loads. Together, these resources have the potential to yield a truly fast and flexible DR resource.

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