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Opportunities for Energy Efficiency and Automated Demand Response in Industrial Refrigerated Warehouses in California

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Disclaimer

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Abstract

This report summarizes the Lawrence Berkeley National Laboratory's research to date in characterizing energy efficiency and open automated demand response opportunities for industrial refrigerated warehouses in California. The report describes refrigerated warehouses characteristics, energy use and demand, and control systems. It also discusses energy efficiency and open automated demand response opportunities and provides analysis results from three demand response studies. In addition, several energy efficiency, load management, and demand response case studies are provided for refrigerated warehouses.

This study shows that refrigerated warehouses can be excellent candidates for open automated demand response and that facilities which have implemented energy efficiency measures and have centralized control systems are well-suited to shift or shed electrical loads in response to financial incentives, utility bill savings, and/or opportunities to enhance reliability of service. Control technologies installed for energy efficiency and load management purposes can often be adapted for open automated demand response (OpenADR) at little additional cost. These improved controls may prepare facilities to be more receptive to OpenADR due to both increased confidence in the opportunities for controlling energy cost/use and access to the real-time data.

Keywords: Open automated demand response, energy efficiency, controls, refrigerated warehouses, food processing, demand response

Executive Summary

Introduction

Since 2006, the Industrial Demand Response Team, which is part of the Demand Response Research Center (DRRC) at Lawrence Berkeley National Laboratory (LBNL), began researching and evaluating demand response (DR) opportunities in industrial facilities. First, the research team collected and analyzed data on recommended DR strategies included in utility integrated audits. Second, the research team supported several California electric utilities and their contractors to identify potential OpenADR industrial participants and provided technical assistance in evaluating DR sites. Third, the research team conducted in-depth analyses of industrial sectors that appeared to have OpenADR potential and analyzed industrial DR technical capacity.

This effort builds on ongoing DRRC research, development, demonstration, and deployment activities of the DRRC related to Open Automated Demand Response (OpenADR). OpenADR is a set of continuous and open communication signals and systems provided over the Internet to allow facilities to automate their demand response with no "human in the loop." OpenADR is intended to standardize DR event information between DR Service providers (utility/ISO) and consumers (facilities/participants and aggregators).

In 2008, industrial refrigerated warehouses were selected as a focus of LBNL's OpenADR research because:

- Refrigerated warehouses are energy-intensive facilities that have significant power demand during the utility peak periods,
- Some refrigerated warehouse facilities already have in place controls for load management programs as well as experience in applying energy efficiency measures which provides a base for participation in OpenADR programs,
- The number of processes conducted in these facilities is limited and the processes are well understood,
- Most refrigerated warehouse processes are not sensitive to short-term (2–4 hours) lower power operation and demand response activities are not disruptive to facility operations, and
- The experience with some of the demand response strategies proven successful in commercial buildings may be applicable to these facilities.

This research studies the potential opportunities and barriers related to implementing OpenADR in the refrigerated warehouses sector, both practical and perceived. Some of these include: the wide variation in loads and processes, resource-dependent loading patterns that are driven by outside factors such as customer orders or time-critical processing, the perceived uncertainties associated with the control capabilities for implementing OpenADR strategies, and concerns about interrupting the scheduled processes and assuring product quality.

Refrigerated warehouses have the potential to benefit from the implementation of demand response and energy efficiency strategies. However, there is little comprehensive research that summarizes the available information describing the energy savings potential and how to target the refrigerated warehouses for demand response activities. Also, the incomplete knowledge and perceived difficulty of demand response among facility managers limits the participation in demand response programs (Quantum Consulting Inc. 2006). This report seeks to fill this knowledge gap by describing the energy end uses within refrigerated warehouses, the technologies used to control energy use, and how equipment and facility controls can be targeted for energy efficiency and demand response strategies. The report also includes a compilation of refrigerated warehouse energy efficiency and demand response case studies that detail individual strategies and their effects, as well as an energy end-use analysis of data collected from facilities that participated in demand response events.

Research Goals

California's industrial sector represents 20 percent of the base electricity peak demand, or approximately 8600 MW. Preliminary estimates indicate that 30–40 percent of industrial loads may be open automated demand response (OpenADR) candidates (PIER Demand Response R&D Strategy 2006).

The goal of the DRRC industrial research is to facilitate deployment of industrial OpenADR that is economically attractive and technologically feasible, can carry out load reduction strategies using customized pre-programmed DR strategies that can be activated upon receiving DR event or price signals, and can maximize load reduction savings without affecting operations. The goal in conducting this research is to provide policy makers, utilities, and facility management with the information necessary to design and operate energy efficient refrigerated warehouses capable of participating in demand response events. Facilities participating in continuous energy management programs will be more, not less, likely to initiate demand response and load management actions (Piette 2008) because they will have a more complete understanding of:

- How energy efficiency and demand response can result in immediate and extensive savings for refrigerated warehouse facilities, as well as reliability in energy services,
- The benefits of demand response for the facility,
- How demand response events affect regular operations within their facility (e.g., cold storage temperature floating or pre-cooling),
- The types of technology installations or retrofits needed for energy efficiency and demand response and how existing controls and automation strategies for energy efficiency and load management can also be used for open automated demand response,
- How to plan different strategies for demand response events,
- How individual components of the refrigeration system can be controlled during a demand response event, and

- The limitations and risks of demand response depending on their facility technologies, energy-use profile, and characteristics of stored products

Methods

This report was compiled after extensive research on literature concerning refrigerated warehouse specifications, demand response strategies, and energy efficient upgrades. The literature search included 54 sources ranging from peer-reviewed studies describing the demand response-related technologies and equipment controls to case studies of energy efficiency and demand response applications. While the literature provides relatively comprehensive information about the basic equipment and controls included in the design of the refrigerated warehouse facilities, it has little information about the demand response potential of the existing controls and equipment. The study utilized LBNL staff experience from participating and planning demand response programs for several facilities, including demand control related discussions with facility technical staff. In addition, the study used information from recent utility reports to describe the potential demand response strategies in refrigerated warehouses.

Data from field studies of three refrigerated warehouses sites that participated in a series of demand response events were analyzed in order to understand which strategies were most successful in achieving load reduction. These sites participated in either a Critical Peak Pricing program (CPP) or Demand Bidding Program (DBP). The study compared end use demand during the peak period of the demand response event on event days against the calculated baseline.

Key Findings

This research indicates that refrigerated warehouses which have implemented energy efficiency measures and have centralized control systems are likely to be successful in implementing OpenADR. In 2007 and 2008, the first seasons of active recruitment in this sector, a total of 35 industrial facilities agreed to participate in OpenADR in PG&E and SCE territory, representing a total enabled OpenADR capacity of nearly 40 MW (Kiliccote 2008). Four of these facilities are refrigerated warehouses, which have committed to a load reduction of about one MW (Kiliccote 2008). These load reductions were accomplished through a combination of strategies, such as shedding cold storage, reducing lighting and HVAC loads in non-essential areas, shifting cold storage loads through pre-cooling, and rescheduling battery chargers load to off-peak hours. The main reasons for the sites' participation in automated demand response programs were to take advantage of utility incentives, improve facility power system reliability, and save on utility bills.

Key Finding: Applying demand response strategies in industrial refrigerated warehouses could reduce California's peak demand.

- The electrical load from California's refrigerated warehouses is about 360 MW (Prakash B. & R. Paul Singh 2008). The results from four California refrigerated warehouses that participated in demand response programs in 2008 showed moderate potential demand savings in the 200–400 kW range. This results in a theoretical potential demand reduction in California ranging from 43–88 MW, based on the approximately 220 large refrigerated warehouses in California, with a capacity of 12 million cubic meters (412 million cubic feet) (USDA 2008). Assuming a relatively modest 20 percent participation rate, the demand reduction will range from 9–18 MW in California without any noticeable impact on operations. Overall, the demand reduction will be 3.7–7.3 W/m^3 (0.11–0.21 W/ft^3).

Key Finding: Cold storage provides a significant potential for load reduction, but other facility end uses may also offer opportunities for load reduction.

- Data from three cold storage demand response participants demonstrated that load reduction could be achieved through curtailment of cold storage processes, and other loads, such as HVAC and lighting. One analyzed facility was able to reduce its load by 29 percent with cold storage reductions. Another site was able to reduce its load by 26 percent by reducing other end use demand. Cold storage was shown to comprise a large percent of the electricity load in refrigerated warehouses, making it a primary target for load shedding or shifting.

Key Finding: Product temperature limitations can restrict the load reduction magnitude.

- Refrigerated warehouse equipment must be controlled within design and operational constraints. Facilities must be careful to maintain temperatures within the specified ranges of different product characteristics during demand response events.

Key Finding: Facility control systems are suitable for automated demand response when they are integrated into larger centralized control systems.

- Specific technologies allow for capacity adjustment or temperature settings which can be modified to reduce energy demand during demand response events. Ideally, these components are connected to integrated supervisory control systems which allow for maintaining facility operations and building services while reducing demand.
- Some refrigerated warehouses have controls that can support OpenADR. Existing industrial controls, if DR enabled, hold significant promise for integration into an OpenADR framework. Understanding of the facility equipment and system design and operational constraints is a key component of effective OpenADR.
- Limited field data indicates that Distributed Control Systems are the prevalent type of control in refrigerated warehouses in California. The CEC industrial controls survey, results of which are expected in 2009, will provide more indications about the current state of controls in California refrigerated warehouses.

Key Finding: Energy efficient and load management technologies may enable successful participation in demand response events.

- Individual equipment controls and centralized control systems that are installed for energy efficiency and load management purposes may also provide the necessary conditions and allow the degree of control necessary to conduct demand response activities.
- Improved envelope insulation of the cold storage areas can limit temperature changes during demand response events. Additionally, appropriately designed airlock loading dock doors can prevent temperature fluctuations and moisture infiltration.

Next Steps

The next phase of the refrigerated warehouses report will involve the following steps:

1. Utilize the Industrial Refrigerated Warehouse Technical Advisory Group to enhance the information in this report, and
2. Utilize inputs from CEC and key experts to finalize the report findings.

Future Research

This research has identified opportunities for additional study that would build on the body of knowledge in this report. It represents a mid-point in this research effort and the future work should consider the following:

1. Utilize the results of the Industrial Controls Survey and discussions with control experts to better understand existing controls capability in refrigerated warehouses.
2. Continue performing field studies in 2009 to add to the body of knowledge about OpenADR implementation experience in the refrigerated warehouses sector; collect data to quantify the impact and relationship between parameters that affect the success of automated demand response strategies, including the impact of product mass, storage facility envelope, cooling capability, and varying ambient conditions.
3. Continue to survey the literature for case studies and technology advances that might affect OpenADR potential.
4. Coordinate with California utilities to develop a better understanding of the life cycle of the existing stock of refrigerated warehouses, both for equipment and structural.
5. Use the findings from this report and the above activities to develop the Refrigerated Warehouses Demand Response Strategy Guide, and
6. Develop DR Quick Assessment Tool for Refrigerated Warehouses building on office and retail tools. This would benefit refrigerated warehouses operators by providing them with the capability to assess facility performance within some range of performance criteria thus enhancing their capabilities to implement OpenADR.
7. Scaling and standardizing the OpenADR for control systems to apply to Refrigerated Warehouses to reduce implementation cost, and increase DR reliability and effectiveness.

8. Improve understanding of how facility operations impact the effectiveness of DR strategies and identify the best operation practices and behaviors to enhance the impact of DR activities.

1.0 Introduction

Background and Overview

Demand Response (DR) is a set of actions taken to reduce electric loads when contingencies, such as emergencies or congestion, occur that threaten supply-demand balance, and/or market conditions occur that raise electric supply costs. DR programs and tariffs are designed to improve the reliability of the electric grid and to lower the use of electricity during peak times to reduce the total system costs (Flex your Power 2008; Pacific Gas and Electric Company 2008). Open Automated Demand Response (OpenADR) is a set of standard, continuous, open communication signals and systems provided over the Internet to allow facilities to fully automate their demand response activities without the need for manual actions. Automated demand response strategies can be implemented as an enhanced use of upgraded equipment and facility control strategies originally installed as energy efficiency measures. Conversely, installation of controls to support automated demand response may result in improved energy efficiency through real-time access to operational data (Kiliccote 2008; Piette 2008).

The Industrial Demand Response Team, which is part of the Demand Response Research Center (DRRC) at Lawrence Berkeley National Laboratory (LBNL) formed in 2006. The Industrial Team collects and analyzes data on DR recommendations included in utility integrated audits, works with utilities and their contractors to identify OpenADR industrial participants, provides technical assistance in evaluating OpenADR sites, conducts in-depth analyses of industrial sectors that appear to have OpenADR potential, analyzes industrial OpenADR technical capacity, performs OpenADR testing at selected sites and reports on R&D opportunities.

Implementing industrial OpenADR presents a number of challenges, both practical and perceived. Some of these include: the wide variation in loads and processes, resource-dependent loading patterns that are driven by outside factors such as customer orders or time-critical processing, the perceived uncertainties associated with the control capabilities for implementing OpenADR strategies, and concerns about interrupting the scheduled processes and assuring product quality.

Refrigerated warehouses have the potential to benefit from the implementation of demand response and energy efficiency strategies. However, there is little comprehensive research that summarizes the available information describing the energy savings potential and how to target the refrigerated warehouses for demand response activities. Also, the incomplete knowledge and perceived difficulty of demand response among facility managers limits the participation in demand response programs (Quantum Consulting Inc. 2006). This report seeks to fill this knowledge gap by describing the energy end uses within refrigerated warehouses, the technologies used to control energy use, and how equipment and facility controls can be targeted for energy efficiency and demand response strategies. The report also includes a compilation of refrigerated warehouse energy efficiency and demand response case studies that detail individual strategies and their effects, as well as an energy end-use analysis of data collected from facilities that participated in non-automated DR events. Finally, this report also includes a case study of preliminary findings from one of the first refrigerated warehouses participating in OpenADR.

Research Scope

Historically, industrial DR programs have engaged facilities to participate in manual or semi-automated demand response largely in response to reliability issues. The DRRC Industrial Team began conducting research on strategies for engaging California industry in OpenADR, with a particular focus on the practical potential of 1) small, frequent sheds or shifts that could be accommodated without any significant disruption in facility operations and 2) the decision-making strategies that facilities might apply in evaluating the attractiveness of a price responsive (as opposed to reliability) shed or shift. The research seeks to build on lessons from the successful implementation of DR in the commercial sector as well as knowledge acquired by the CEC, LBNL, and others concerning the energy use patterns and DR potential for California industry.

The goal of the DRRC industrial research is to facilitate deployment of industrial OpenADR that is economically attractive and technologically feasible and to increase DR reliability and effectiveness. This longer-term study is focused on several key research questions, provided below.

Refrigerated Warehouses Key Research Questions

1. **Where is the potential to shed or shift electricity use in refrigerated warehouses?**
    - Which end uses have the greatest potential to shed or shift during peak periods?
2. **What is the functional capability of refrigerated warehouses industrial sector to implement OpenADR?**
    - What are the control gaps and the associated cost of implementing OpenADR?
3. **What are the market and operational barriers to the implementation of reliability and price-responsive industrial DR?**
    - Do refrigerated warehouses' energy managers understand economic and societal benefits of DR?
    - What roles do price and incentives have in the decision making process?
    - What are the areas of tension between DR and refrigerated warehouses operation?
4. **What is the role of industrial OpenADR in the state's goal to provide reliable and climate-friendly electricity at a reasonable cost to California consumers?**
    - Does participation in OpenADR by refrigerated warehouses assist in promoting industrial load management and energy efficiency in these facilities?

The overall industrial sector key research questions include several additional topics that are beyond the scope of in this study. Those include: What are the market trends in industrial controls that support OpenADR? Do advances in control technologies make specific sectors or systems attractive candidates for OpenADR? What are the technology gaps that might benefit from public R&D?

Benefit to California

This report focuses on energy efficiency and demand response applications within large[1] industrial refrigerated warehouses because refrigeration systems are used in a wide range of industrial applications and account for some of the largest electrical loads in food processing facilities. In 2007, the United States refrigerated warehouse storage capacity was about 94 billion cubic meters (3.32 billion gross cubic feet) (USDA 2008). Within this amount, California had the largest fraction of that capacity: a value of 12 million cubic meters (412 million cubic feet) (USDA 2008). PG&E found that, if energy efficient insulation and appropriate control specifications are put into place in California refrigerated warehouses, electricity consumption would be reduced by 15.6 GWh per year (Pacific Gas and Electric Company 2006).

The electrical load from California's refrigerated warehouses is about 360 MW (Prakash B. & R. Paul Singh 2008). The results from four California refrigerated warehouses that participated in demand response programs in 2008 showed moderate potential demand savings in the 200–400 kW range. This results in a theoretical potential demand reduction in California ranging from 43–88 MW, based on the approximately 220 large refrigerated warehouses in California, with a capacity of 12 million cubic meters (412 million cubic feet) (USDA 2008). Assuming a relatively modest 20 percent participation rate, the demand reduction will range from 9–18 MW in California without any noticeable impact on operations. Overall, the demand reduction will be 3.7–7.3 W/m^3 (0.11–0.21 W/ft^3).

Report Organization

This section describes the context, rationale, and potential for demand response in industrial refrigerated warehouses, research scope and key questions, and the benefit of California.

- **Section 2, Refrigerated Warehouses Characteristics,** describes the basics of refrigerated warehouses.
- **Section 3, Energy Use,** summarizes the energy use in refrigerated warehouses.
- **Section 4, Controls,** details the existing controls in these facilities.
- **Section 5, Energy Efficiency and Automated Demand Response Opportunities,** outlines the potential for energy efficiency and demand response measures.
- **Section 6, Analysis of Demand Response Studies,** discusses the analysis of data from the implementation of demand response strategies in three California refrigerated warehouses.
- **Section 7, Case Studies,** describes case studies of energy efficiency and load management efforts to date.
- **Section 8, Conclusions,** provides conclusions.

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[1] The subjects of this report are facilities which currently qualify for Open Auto DR participation, which requires a demand reduction of 200 kW or more.

- **Section 9, References,** lists references.
- **Appendices** provide supporting information.

2.0 Refrigerated Warehouses Characteristics

The 2006 American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Handbook on refrigeration defines refrigerated warehouses as any building or part of a building that used refrigeration to control storage conditions. The two major categories of storage facilities are coolers that store products at temperatures above 0°C (32°F) and freezers that store products at temperatures under 0°C (32°F). They can also be classified as small, intermediate, and large storage rooms ranging from small rooms utilizing prepackaged refrigerator units to large cold storage cooler/freezer warehouses (Becker 2005). Further divisions of refrigeration categorization include:

- Controlled atmosphere facilities for long-term fruit and vegetable storage
- Coolers from 0°C (32°F) and above storage
- High-temperature freezers at -2.8 to -2.2°C (27–28°F)
- Low-temperature storage for general frozen products at -20.6 to -28.9°C (-5 to -20°F)
- Low-temperature storage that includes extra storage space for products above -17°C (0°F)(American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) 2006).

The total refrigerated warehouses storage capacity in the United States is about 94 billion cubic meters (3.32 billion gross cubic feet) (USDA 2008). Within this amount, California had the largest fraction of that capacity: a value of 12 million cubic meters (412 million cubic feet) in approximately 220 refrigerated warehouse facilities (Prakash B. & R. Paul Singh 2008; USDA 2008). Modern refrigerated storage facilities usually have a volume range of 28,000 to 85,000 cubic meters (one million to three million cubic feet) (Becker 2005). However, the USDA report does not provide information about the magnitude of the electrical load of these facilities, but it appears that this value refers to large facilities only. This assumption is supported by a Southern California Edison (SCE) report (Table 1) which indicates that in their territory, there are only 95 refrigerated warehouses with a capacity above 1000 kW.

Table 1. Distribution of Southern California Edison Refrigerated Warehouses by Load

Load Capacity	Number
<100 kW	14
100-199 kW	10
200-499 kW	127
500-999 kW	39
>1000 kW	95

Source: Personal Communication. Haiad, Carlos. Southern California Edison. "Data on Refrigerated Warehouses." 2 February 2009.

Table 2 shows the distribution of refrigerated warehouses by size and ownership type in the United States in 2007.

Table 2. Distribution of United States Refrigerated Warehouses by Size and Ownership

Size cubic meters (cubic feet)	Public	Private	All
(0-499,999)	117	369	486
(500,000-999,999)	97	114	211
(1,000,000-2,499,999)	212	128	340
(2,500,000-4,999,999)	206	76	282
(>5,000,000)	160	22	182
Total	792	709	1,501

Source: Capacity of Refrigerated Warehouses: 2007 Summary. USDA. 2008.

Refrigerated warehouse facilities are classified as public warehouses, which store food for clients at a certain rate, and private warehouses, which typically encompass the role of producer, manufacturer, packager, and refrigerator for products. Semi-private facilities usually include a private warehouse section with additional space for public storage. Some warehouses have expanded their capabilities for revenue purposes and also operate as distribution centers (Gottlieb 2006). They can include farms, fruit, and vegetable freezing facilities, storage facilities for manufactured food products, and dairy and wine processors. The energy loads in these facilities vary since many of their products are seasonal. However, energy loads for all refrigerated warehouse types typically peak during summer months when agricultural facilities face heavy demands and refrigeration systems must work harder to compensate for warmer weather (Pacific Gas and Electric Company 2005).

2.1. Refrigerated Warehouse Design Characteristics

Large refrigerated warehouses are typically custom-designed. The main design considerations are mostly related to wall and roof types, shell insulation, and the refrigeration system. The refrigeration system design involves sizing of the condenser, compressor and evaporator, determining power capacity, and controls to maintain efficient operation and sufficient capacity. Refrigeration systems maintain temperatures settings that could be used for demand response events. Improved shell insulation reduces refrigeration equipment load and helps maintain temperatures so that warehouses can float temperatures during demand response events without compromising product quality (Pacific Gas and Electric Company 2007).

The various storage areas in a refrigerated warehouse require different levels of insulation. Freezer areas require more insulation, with a typical construction of 0.13 meter or 0.15 meter (5-inch or 6-inch) expanded urethane metal clad panels which have thermal resistance values ranging from R-32 to R-56 for freezer walls (Pacific Gas and Electric Company 2007). Freezer floors are constructed from glycol tubes set in mud slab and covered with 0.1 meter (4-inch) of rigid styrene covered with 0.15 meter (6-inch) of reinforced concrete, with insulation ranging from R-18 to R-30 (Pacific Gas and Electric Company 2007). Freezer ceilings are typically insulated with 0.13 meter (5-inch) Isocyanurate, resulting in R-values from R-31 to R-50 (Pacific Gas and Electric Company 2007). In facilities containing both cold storage and frozen storage areas, the cold storage areas often are built with the same insulation as the freezer areas.

In facilities without frozen storage areas, less insulation is used. Ceilings in cold storage areas are typically constructed from wood frame plywood with 0.1 meter (4-inch) blown-on urethane insulation achieving R-values of R-24 to R-40 (Pacific Gas and Electric Company 2007). Cold storage walls consist of either 0.1 to 0.13 meter (4–5-inch) expanded urethane metal clad panels or concrete sandwiched panels achieving R-values of R-23 to R-40 (Pacific Gas and Electric Company 2007). The R-values for roof insulation ranges from R-30 to R-50 (Becker 2005). Cold storage area floors are typically made of uninsulated concrete.

The majority of refrigerated warehouses have a loading docks section in addition to separate cooling and freezing sections. Loading docks can create a significant increase in refrigerated warehouse energy demand if they are not monitored for moisture infiltration. Air units are used to dehumidify the air in loading docks and discharge it over freezer doors to inhibit moisture infiltration; this air must be reheated to extract moisture from the air (Concepts and Designs Inc. 2007). Otherwise, the moist air could enter the cold and frozen storage, where it will impose additional strain on the refrigeration compressor. Monitoring loading docks and removing moisture from the air before it reaches the refrigeration sections can result in significant energy and demand savings for refrigerated warehouses (Turpin 2000).

Based on their extensive energy use and large-scale presence in the United States, and specifically California, it is evident that refrigerated warehouses are good candidates for demand response strategies. However, the success of these strategies hinges on the ability of the facilities to maintain adequate temperature ranges to prevent product damage and to construct warehouses capable of maintaining adequate temperatures without absorbing unnecessary heat. Once these factors are taken into account, it is possible to start developing demand response strategies for the refrigeration system itself and for the other energy-using components within the warehouse.

2.2. Refrigerated Warehouses Operation Limitations

Refrigerated warehouses store many different types of foods that require different temperature ranges. Some foods can be sensitive to temperature changes. If temperatures rise too high, deterioration may occur. Additionally, drastic fluctuations in temperature may also cause warming and recooling, resulting in ice crystal growth within the products (U.C. Davis). This is important because when a facility participates in a demand response event, the reduced use of refrigeration equipment can cause the temperatures within storage areas to vary. In a report on energy efficiency in refrigerated warehouses, PG&E suggested that frozen packaged products, frozen juices, and frozen products that do not require a minimum temperature are good candidates for demand response strategies, since they can tolerate a 5°F temperature drift (Pacific Gas and Electric Company 2007). In contrast, cooled products may not tolerate temperature variations larger than 2–3°F and humidity variations greater than 3–5% (American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) 2006). How quickly this drift occurs depends on the thermal mass (amount of product) stored, the traffic within the storage areas, the heat generated by lighting, the evaporator fan operation and the insulation performance. The report estimates that a 5°F drift could take around 4 to 6 hours (Pacific Gas and Electric Company 2007). Table 3 shows recommended temperatures for freezing and storing different types of foods. These temperature ranges should be maintained even as the refrigeration load varies due to outgoing or incoming products movement.

Additionally, planned demand response strategies must ensure facility operation maintain the temperature of stored products within the permissible temperature range. Warehouse construction makes this possible – increased insulation prevents temperature gain and loading dock air units prevent energy wasteful moisture infiltration that requires additional energy use.

Table 3. Recommended storage and transit temperatures for food products

Type	Temp Ranges	Foods
Cold Storage	12.8 to 17.8°C (55 to 64°F)	Ginger, Pumpkin, Tomato, mature green, Cassava, Sweet potato, Taro, Yam, Breadfruit, Grapefruit
	7.2 to 10°C (45 to 50°F)	Basil, Eggplant, Long bean, Okra, Squash, Watermelon, Capsicum (bell pepper), Cranberry, Grapefruit, Lemon, Lime, Pineapple, Tamarillo, Tangelo, Ugli fruit
	3.9 to 7.2°C (39 to 45°F)	Beans, Cactus leaves, Cucumber, Chilli, Potato, Southern peas, Tomatillo, Blood orange, Prickly pear, Jujube, Kumquat, Mandarin, Olive, Orange, Persimmon, Pomegranate, Tamarind, Tangerine, Meat carcase, side, quarter or bone-in, Game, Edible Offal, Vacuum Packed Goods, Poultry (5°C) (41°F), Eggs (5°C) (41°F)
	0 to 3.9°C (32 to 39°F)	Onion, Garlic, Asparagus, Bok choy, Broccolini, Broccoli, Brussels sprouts, Cabbage, Carrot, Cauliflower, Celery, Chard, Chicory, Chinese cabbage, Collards, Cut vegetables, Endive, Green onion, Herbs (not basil), Kailon, Kale, Leek, Lettuce, Mint, Mushroom, Mustard greens, Parsley, Parsnip, Snow pea, Spinach, Sweet pea, Turnip greens, Watercress, Artichoke, Bean Sprouts, Beet, Celeriac, Horseradish, Jerusalem, Artichoke, Kohlrabi, Radish, Rhubarb, Shallot, Sweet corn, Turnip, Waterchestnut, Bitter melon, Blackberry, Blueberry, Cherry, Coconut, Currant, Date, Gooseberry, Grape, Longan, Loquat, Lychee, Orange, Raspberry, Strawberry, Apple, Apricot, Avocado (ripe), Rockmelon, Cut fruits, Fig, Kiwifruit, Nectarine, Peach, Nashi Pear, Pear European, Plum, Prune, Quince, Milk, Yoghurt, Cream, Butter, Margarine, Cheese, Meat carcase, side, quarter or bone-in, Meat portions, bones, carton meat, Rabbit, Uncooked Processed Meat (e.g., sausages, rissoles), Cooked Processed Meat (e.g., Ham, Luncheon Meats) Fermented Uncooked Processed Meat (e.g., Salami, Mettwurst), Green or Cooked Seafood
Frozen Storage	-17.8 to 0°C (0 to 32°F)	Poultry (-15°C) (5 °F)
	-5.6 to -17.8°C (-22 to 0°F)	Butter (-27.8 to -20°C) (-18 to -4°F), Cheese (-27.8 to -20°C) (-18 to -4°F), Ice cream (-30 to -22°C) (-22 to -8°F), Fresh Meat Product (-12.8 °C) (-9°F), Seafood (Abalone, Cockles, Crab, Fin fish, Lobsters, Marron, Octopus, Oysters, Prawns, Scallops, Shark, Squid, Tuna (except Sashimi), Yabbies) (<-17.8 °C) (< 0°F)

Source: Government of South Australia Transport and Handling of Perishable Products in Remote Areas of South Australia, Department for Transport Energy and Infrastructure. 2003.

3.0 Energy Use

In order to determine energy efficiency and demand response strategies for industrial refrigerated warehouses, the facility processes and energy use must be carefully examined. This section describes the general components of a refrigeration system and how they interact, the differences between freezer and cooler types of refrigeration systems, and the other energy end uses besides the refrigeration system that are situated in a refrigerated warehouse.

The electrical load from refrigerated warehouses in California is about 360 MW (Prakash B. & R. Paul Singh 2008). PG&E found that, if energy efficient insulation and appropriate control specifications are put into place in California refrigerated warehouses, electricity consumption would be reduced by 15.6 GWh per year (Pacific Gas and Electric Company 2006).

Additionally, the results from four California refrigerated warehouses that participated in demand response programs in 2008 showed moderate potential demand savings in the 200 – 400 kW range for each facility (Kiliccote 2008). This results in a theoretical potential demand reduction in California ranging from 46 to 91 MW. However, assuming only 20% participation, the demand reduction will range from 9 to 18 MW in California.

3.1. The Refrigeration System

A basic refrigeration system consists of an evaporator, a compressor, a condenser and an expansion valve. The refrigerant is looped though the system components. Many different substances can be used as refrigerants, including air, water, carbon dioxide, man-made refrigerants, and ammonia. The type of refrigerant used depends on the pressures and temperatures needed in the process. Ammonia is the most commonly used refrigerant for food processing and storage facilities and is an effective refrigerant, which allows ammonia compressors to be smaller or to operate at slower speeds and require less maintenance than other compressors (Naval Facilities Engineering Command 1986).

The general refrigeration cycle, seen in Figure 1, allows for energy efficiency opportunities, which involves the controls of the individual components. The following outlines the refrigeration process: at the evaporator stage, the refrigerant is located in an evaporator coil at low pressure and temperature. Fans blow warm air over the evaporator, causing the refrigerant to vaporize, while the air is cooled due to heat loss. The vaporized refrigerant is then moved into the compressor, where the vapor is compressed, raising its pressure and temperature. Next the high-pressure, high-temperature vapor enters the condenser, where fans blow cooler air over the warm vapor, partially cooling the vapor, condensing it into liquid form and raising the air temperature. Lastly, the still high-temperature liquid refrigerant passes through the narrow opening of the expansion valve, which causes a fraction of the refrigerant to vaporize, extracting heat from the remaining liquid refrigerant. The refrigerant has now returned to the low-temperature and low-pressure state for recirculation (Wilcox 2004).

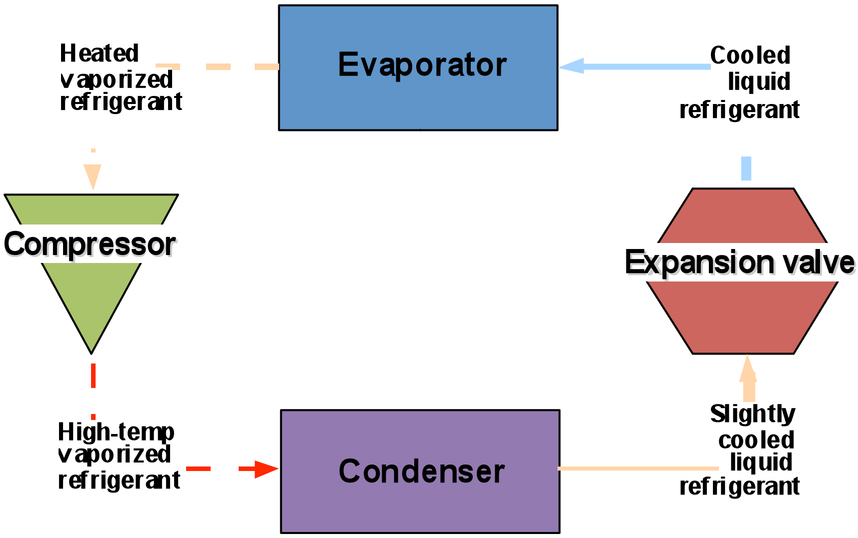

Figure 1. Refrigeration cycle

3.2. Freezers and Coolers

Based on the temperature ranges maintained, refrigerated warehouses can be grouped into two categories: cold storage (coolers) and frozen storage (freezers). Cold storage areas typically maintain temperatures between 0–10 ˚C (32–50˚F), while frozen storage areas maintain temperatures lower than 0˚C (32˚F). A survey of refrigerated warehousing in the United States asserted that freezer space comprises 78% of total warehouse area while cooler space occupies the remaining 22% (Prakash B. & R. Paul Singh 2008).

Frozen storage and cold storage facilities rely on the same technologies, but operate differently. Frozen storage areas, or freezers, typically rely on electric or hot gas defrost to prevent ice build-up on refrigeration coils. Typical freezer procedure involves cycling evaporator fans off while compressors are off. Cold storage areas, or coolers, have shorter operation periods than freezers and have greater load variation. Different control strategies must be applied in freezers and coolers (Federal Energy Management Program 1998). Though both freezers and coolers rely on compressor technology, freezers typically use two-stage compressors, while coolers use single-stage compressors (McMullan). Two-stage compression is more efficient than single-stage because compression is most efficient when the refrigerant is at a saturation temperature (Wilcox 2004). The more gradual pressure change of the two-stage compression also results in less air leakage, greater efficiency, higher pressure capabilities, and reduced wear and tear on the compressors. When operated at full-load capacity, a single stage compressor consumes about 18–19 kW per 2.8 cubic meters per minute (100 cubic feet per minute) delivered, whereas two-stage systems consume about 16–17 kW per 2.8 cubic meters per minute (100 cubic feet per minute) delivered, resulting in 11–13% energy savings. If two-stage compressors are equipped with variable speed drives, they are also efficient when operating at partial load (Harish Shah and Mark Pfeifer 2006). Table 4 summarizes the differences between freezers and coolers.

Table 4. Freezer and Cooler Summary

	Defrost Type	Products Stored
Freezers <-18°C (0°F) Two-stage Compressors	Heat defrosting – can be used for cold storage rooms below freezing temps, heat is supplied by water spray, hot gas or electric heating and air fans are turned off to prevent moisture distribution Water spray is economical, but takes more time, is used for rooms above -18°C (0°F) Hot gas uses compressed vapor from the compressor to heat the evaporator Electric defrost uses electric heating elements built into the evaporator, is rapid, efficient and good for low temperature applications, has low initial cost, but operating costs can be high	Poultry (-15°C) (5°F), Butter (-28 to -20°C) (-18 to -4°F) Cheese (-28 to -20°C) (-18 to -4°F) Ice cream (-30 to -22°C) (-22 to -8°F) Fresh Meat Product (-23°C) (-9°F) Seafood (< -18°C) (< 0°F)
Coolers -18−10°C (0– 50°F) Single stage compressors	Brine spray – continuously spraying brine on evaporator coils prevents frost formation, adjustments must be made since brine concentration decreases with moisture pick-up Propylene glycol brine defrosts system as low as 1.7°C (35°F) Sodium chloride can be used for systems -12°C (10°F) and above	Fruit, vegetables, Meat, Poultry (5°C) (41°F), Eggs (5°C) (41°F), Milk, Yoghurt, Cream, Butter, Margarine, Cheese, Green or Cooked Seafood
	Air defrosting – can be used for cold storage rooms above freezing temps, air fan and evaporator melts frost during off-cycle, not desirable for low-humidity applications since moisture is produced due to condensation	

Source: Department of the Navy - Naval Facilities Engineering Command (1981). Refrigeration Systems for Cold Storage.

3.3. Energy End Uses

Within refrigerated warehouses the main energy end-uses are product refrigeration and processes such as lighting, maintaining water temperature, HVAC, manufacturing processes and charging forklift batteries (Pacific Gas and Electric Company 2007). Figure 2 shows the share of facility load accounted for by equipment end use in a typical refrigerated warehouse. The main energy end-uses in refrigerated warehouses are product refrigeration in cold and frozen storage areas and buildings services (Pacific Gas and Electric Company 2007). Refrigeration accounts for over half of a typical refrigerated warehouses' end use energy. Electric defrost also contributes a significant portion of the energy use in industries. All other services total about 25% of the end use energy in industrial refrigerated warehouses.

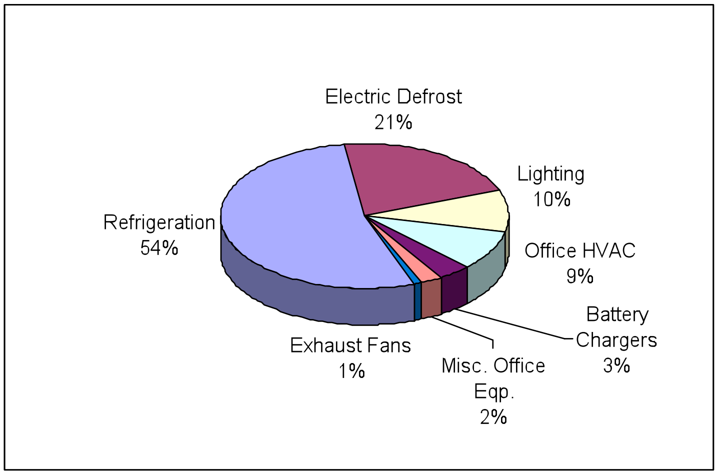

Figure 2. Refrigerated Warehouse End Use Load

Source: National Grid. "Demand Response Programs, Shared Demand Response Sample Audit. 2004.

PG&E conducted a study on refrigerated warehouse energy efficiency opportunities and found that, if recommended energy efficiency steps (as outlined in Section 7: Energy Efficiency and Automated Demand Response Opportunities), were applied for evaporators, compressors, condensers, and the warehouse shell, evaporators would contribute to more than half of overall facility energy savings, compressors would account for 34% of savings, condensers for 12%, and shell measures for 3%. Figure 3 displays these values (Pacific Gas and Electric Company 2007).

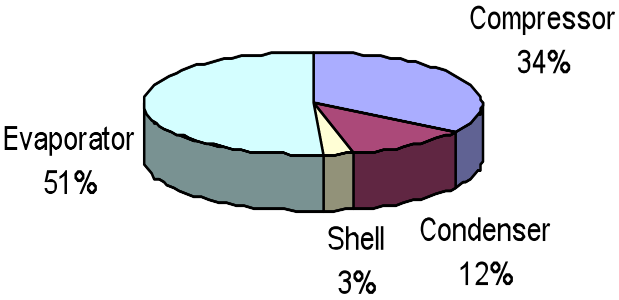

Figure 3. Relative Contribution of Each Measure to Overall Savings

By choosing the most appropriate specifications for these components and having the capability to remotely control this energy intensive equipment, refrigerated warehouses are capable of reducing energy use and demand while maintaining product quality, and increasing equipment reliability. This results in improved opportunities for energy efficiency and demand response.

4.0 Controls

Many refrigerated warehouses have computerized control systems to monitor and control the performance of the refrigeration system components. Computer controls allow key operating parameters such as temperature, pressure, level, flow, oxygen or carbon dioxide concentration, refrigerant, energy use and demand, and production to be monitored (Becker 2005). Several control system types are encountered in refrigerated warehouse facilities: standalone controls, distributed control systems (DCS) and integrated control systems such as Supervisory Control and Data Acquisition systems (SCADA). Standalone controls are the most basic level of systems which control individual equipment operations, mostly HVAC systems, and small processes without requiring direct supervision. DCS are more complex systems that consist of multiple direct control elements. They generally have closed loop controls, resulting in real-time loop data being applied to an industrial controller without human intervention. SCADA systems are measurement and control systems that gather real-time data from remote locations and control equipment and operating conditions at the supervisory level.

Information collected during the assessment of the automated demand response capabilities at a few refrigerated warehouse facilities in California, has shown that DCS are the prevalent type of controls. Some of these facilities have a limited centralized system, used mainly to record the monitored data and control parameters such as temperature set points. The CEC industrial controls survey, results of which are expected in 2009, will provide more indications about the current state and OpenADR potential of controls in California refrigerated warehouses.

Although field work to date has shown a limited use of centralized control systems, this report will focus on SCADA systems which have the best communication capabilities for automated demand response applications in industrial refrigerated warehouses. These communication capabilities make refrigerated warehouses with integrated centralized control systems excellent candidates for OpenADR by bringing together the actions of the individual equipment controls and locally distributed controls. Such integration allows the OpenADR infrastructure to interact with a single control system instead of multiple systems (e.g., DCS), thus creating a cost-effective and easy to manage reliable base for OpenADR implementation.

4.1. Control Technologies

The most basic level of technologies used in refrigerated warehouse facilities is the physical equipment such as pipes, valves, and motors that the control system monitors and controls. Connected to the equipment are actuators and valve controls or breakers that control electrical equipment and convert field input and output (I/O) into action on the equipment. Meanwhile sensors, such as temperature probes or pressure sensors, monitor the action of the actuators or the conditions of the system and convert this information into electrical data. The sensor data is then looped through I/O controllers back to the actuators control. The data from the sensors and from the I/O controllers is called field I/O and consists of an analog voltage or current signal. This is the level at which systems such as SCADA interact with the physical equipment. SCADA systems convert this analog information into digital information.

Figure 4 shows basic components of a SCADA system (using client/server architecture). They may include Remote Terminal Units (RTUs), Programmable Logic Controllers (PLCs), and Proportional Integral Derivatives (PIDs) logic controls, all of which interface with the sensors and actuators for compressors, fans, pumps, valves, and motors (Techni-Systems 2003). Separate from the SCADA system is the control center, also called master terminal unit (MTU), where system data is stored and where supervisors can manage automation activities via Human-Machine Interfaces (HMI) (M. Berg and J. Stamp 2005).

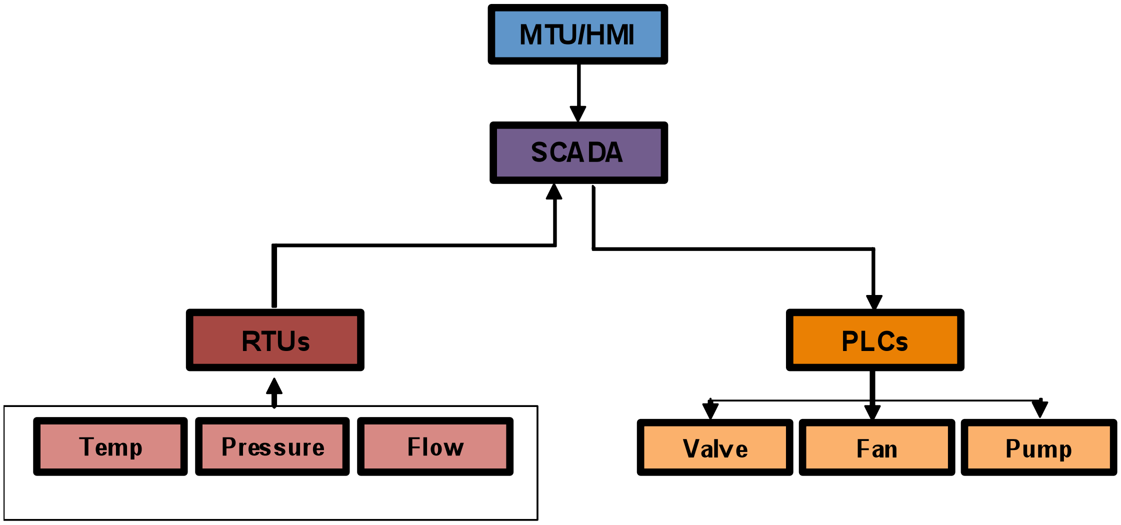

Figure 4. Principal Scheme of a SCADA System

SCADA technology encompasses controls and communication networks that allow for system control (Sandia National Laboratories - The Center for SCADA Security). RTUs are microprocessors that gather data from sensors and communicate it back to SCADA. SCADA collects and processes these data, issues alarms, and controls or allows supervisors to control equipment (Knezev M. and Z. Djekic). PLCs or PIDs receive SCADA instructions, make logical decisions and communicate with equipment to execute instructions.

Companies that manufacture PLCs often provide integrated SCADA systems (Rockwell Automation 2008; Siemens 2008). In many cases, other companies install these technologies and provide the software that allows the facility to control and automate all processes (PowerIT Solutions 2008; Techni Systems 2008).

4.2. Equipment Controls

The controls used in refrigerated warehouses play a key role in the efficient operation of refrigerated warehouse facilities. Advanced control technologies can be beneficial for improving energy efficiency and implementing demand response strategies as well as improving information access and management within the facility. Advanced control systems require less time for checking on equipment, and equipment operates for shorter periods of time which results in reduced facility operation and maintenance costs. Product quality is also improved through well-controlled processes and environment conditions. Such controls reduce the need of manually reading and adjusting equipment (Black 2008).

Different components of refrigeration systems can be retrofitted, upgraded or integrated with control strategies at the system level to enable demand response activities. Within a refrigerated warehouse, all of the refrigeration components have individual controls. Evaporators which have solenoid valve and pressure controls, fan on/off controls, and defrost controls allow adjustment according to zone temperature. Condensers which have pump and fan on/off controls allow for adjustments according to condensing pressure. Compressors which have on/off and unloading controls allow for adjustments according to suction pressure. Simple manual controls allow operators to physically change these settings, while electro-mechanical controls rely on electronic or pneumatic circuitry to adjust settings. Programmable logic controllers (PLCs) perform the same functions as electro-mechanical controls but use solid-state hardware and push-button adjustment. Ideally, PLCs are connected to a more-sophisticated computer control, which allows refrigeration system data to be collected and used to make control decisions through the computer system. This is relevant to energy efficiency and automated demand response measures because supervisors or the SCADA system can adjust system settings to operate most efficiently based on the refrigeration load or on an upcoming demand response event (Wilcox 2004). Additional information on specific refrigeration equipment and their controls can be found in Appendix A: Refrigerated Warehouse Technologies.

Compressor Controls: Compressors account for about 70% of the refrigeration system's total energy load, making efficient controls crucial to facility load management (Smartcool Systems Inc. 2008). A primary method for adjusting refrigeration capacity is to start, stop, or unload compressors. Generally a thermostat or pressure switch is used to control the operation of a compressor (Becker 2005). Compressors sometimes utilize inefficient means of control such as pressure on/off switches or manual controls. Advanced compressor controls have automatic suction controls which set compressors to the optimal suction pressure for the operating conditions. Compressors can also be controlled by managing discharge pressure through the use of floating head pressure controls which is a function of the expansion valve capabilities and condenser capacity. Use of computer controls assists in the appropriate sequencing of compressors to function most efficiently for the specific loads (Techni-Systems 2003). For example, if there is not enough refrigeration demand for an adequate amount of time, compressors will turn completely off. Sequencing allows for direct control of compressors which can instantly reduce the load in the system rather than waiting for indirect unloading of compressors by controlling liquid solenoid valves or suction valves. Compressors can also be controlled more efficiently by applying capacity control with variable speed motors that adjust the compressor motor speed to the most efficient settings for the refrigeration load. This removes the need for the less efficient method of capacity control of changing the slide valve setting. Older compressors can be retrofitted with microprocessor control panels, LCD displays, temperature transmitters, terminals, circuit breakers, and pressure and motor current sensors which allow for better monitoring and control if a demand response event is triggered (McConnell 2007).

Condenser Controls: Continuous monitoring of ambient temperature and relative humidity determines the wet bulb temperature, which is used to set the discharge pressure set point. Temperature data provides a base for making load demand decisions. To maintain optimum condenser capacity control, condenser fans could be controlled using two-speed controls or variable speed technology. Operating the condenser fans at lower speeds uses the entire coil surface area, which allows for more efficient operation than turning fans on/off (Techni-Systems 2003). Variable speed condenser fans allow the condensers to operate at reduced capacity during a demand response event.

Evaporator Fans: Cycling, two-speed, and variable speed control of evaporator fans can reduce electrical energy usage 25–50% and can reduce overall facility demand (Black 2008). Variable speed technology for evaporator fans also provides for more stable temperature control, thus avoiding moisture loss and maintaining product quality. However, operating the evaporator fans at lower speed results in lower air velocity. VFD operation should be controlled to ensure that reducing the air velocity does not result in hot zones in the storage area and higher product temperatures. In addition, variable-speed evaporator fan operation result in less waste heat, which reduces loads on compressors and condensers (Black 2008). Like using variable speed technology with condensers, evaporator fan speed reduction can reduce energy during a demand response event. Many condenser and evaporator fans use two-speed controls that may not be capable of achieving the same savings as VFDs, but are more efficient than single-speed fans.

Electric Expansion Valve: Electric expansion valves are more efficient and easily adjustable than thermostatic expansion valves. Unlike the thermostatic valve, the electric valve does not require a high head pressure and therefore can be operated at a lower pressure and condensing temperature, which results in reduced energy use at higher capacities (Melvin 2006). This is applicable to demand response, in addition to general efficiency, because the valve can be more easily adjusted to reduce flow during peak hours.

Defrost Control: Defrost control monitors the temperature in the evaporator coil and the environment around the coil. Advanced defrost control allows defrosting of evaporator coils when needed, indicated by a temperature set point being reached, as opposed to using a preset defrost schedule. This strategy reduces defrost energy use, and prevents unnecessary defrosting which can affect product quality (Black 2008). Advanced defrost controls could be utilized to shift or delay the defrost process during a demand response event.

Instead of using defrost heaters, it is possible to add a reverse cycle valve to the condenser in conjunction with an electronic control system can reverse refrigerant flow during defrost. The high-temperature refrigerant gas is reversed, resulting in less frost buildup than defrost heaters. This technology can reduce defrost loads by up to 80% (Melvin 2006).

In conclusion, centralized control systems make refrigerated warehouses excellent candidates for OpenADR by bringing together the actions of the individual equipment controls and locally distributed controls. Centralized systems assist communication between higher-level controls and lower-level hardware, facilitating the implementation of automated demand response strategies. Such integration could be a powerful tool for refrigerated warehouses when developing energy efficiency and demand response programs.

5.0 Energy Efficiency and Automated Demand Response Opportunities

Energy efficiency and demand response are key strategies to reducing energy use and demand which represents a large fraction of operating expenses in industrial refrigerated warehouses. Factors such as product sensitivity, electricity use and demand, efficiency characteristics of different equipment, and operating schedules are important when implementing energy-efficiency improvements and automated demand response strategies. Energy efficiency upgrades can improve facility operation and provide a base for the implementation of demand response strategies. OpenADR strategies can be implemented as an enhanced use of upgraded equipment and facility control strategies installed as energy efficiency measures. Conversely, installation of controls to support OpenADR may result in improved energy efficiency through real-time access to operational data (Kiliccote 2008; Piette 2008).

A possible "natural path" to develop OpenADR capabilities in the facilities is to take advantage of the replacement of equipment at the end of its lifetime. This is particularly applicable for key equipment such as compressors, fans, and controls. Individual refrigerated warehouses may look for a window of opportunity in the near future when a substantial fraction of their equipment is nearing the end of its useful life. Such an opportunity may allow the facility to introduce OpenADR enabled equipment on a large scale, thus triggering a technological shift of a magnitude that would not be seen from incremental improvements. While identifying the equipment turnover opportunity in California refrigerated warehouses is beyond the scope of this study, further research into the age distribution for refrigerated warehouse equipment and controls to determine the potential impact of this approach would be a useful follow-up study.

5.1. Energy Efficiency Opportunities

Energy efficiency measures reduce overall energy use and decrease operating costs. Energy efficiency measures also reduce demand by reducing overall energy consumption while providing the same level of service. Some energy efficiency opportunities in refrigerated warehouses relate to improving building envelope insulation, installing fast-acting doors, retrofitting lighting and HVAC systems, variable speed drives, and upgrading to more efficient equipment. Further, regularly scheduled maintenance can improve overall operational efficiency and sustain the impact of efficiency measures.

Insulation: Heating and cooling loads in industrial refrigerated warehouses can be reduced by increasing shell insulation levels. Increasing the insulation levels in ceilings, walls, floors, pipes, and vessels reduces heat losses from the refrigeration equipment or refrigerant piping (Wilcox 2004). Insulation improvement measures in refrigerated warehouses are applied by using extruded polystyrene. For example, during an energy efficiency retrofit, a facility installed six inch thick extruded polystyrene wall and floor insulation, and 0.4 meter (15 inch) thick extruded polystyrene ceiling insulation to reduce heating and cooling losses (Wilcox 2004).

Fast-Acting Doors: Fast-acting doors help reduce air infiltration and heat gain to refrigerated spaces. Fast-acting doors such as bi-parting doors, roll-up doors, and horizontal sliding doors open in seconds and are controlled by magnetic sensing loops in the floor, optical motion detectors, or remotely controllers by forklift operators. These doors save a significant amount of energy compared to manual doors, or strip or air curtains, which only moderately reduce air infiltration (Wilcox 2004).

Lighting & Heating, Venting and Air-Conditioning (HVAC): Lighting and HVAC systems can be retrofitted to decrease facility energy use and demand and reduce overall operating costs. Energy efficient lighting retrofits in refrigerated spaces also decrease refrigeration load by reducing the amount of lighting system-related heat released to cold storage areas (Wilcox 2004).

Variable Frequency Drives (VFDs): Equipment is often oversized for existing loads, because it is designed for peak capacity requirements. This results in the inefficient operation of fans, pumps, compressors at part-load conditions. Reducing equipment operating speed to match the equipment capacity to the load can improve part-load efficiency. Typically, VFDs are used to adjust the speed of electric motors and thus reduce overall energy use by allowing equipment to operate at the necessary speeds. VFDs can be installed on a variety of equipment in refrigeration applications including compressors, and condenser and evaporator fans (Black 2008).

Duty Cycling: Duty cycling involves cycling equipment on and off to match the equipment capacity to the load. The control systems are able to turn down refrigeration equipment in certain zones at scheduled intervals, and restart the refrigeration system if the temperature change exceeds the operational limits (Black 2008). However, frequently cycling equipment, such as compressors or evaporator fans, on and off, may shorten the lifetime of the equipment and increase the maintenance requirements unless measures such as soft-start devices are used.

Demand Refrigeration: Demand refrigeration entails turning off the entire facility's refrigeration system when all of the zone temperatures are reasonably close to the set point for as long as the refrigerated product characteristics allow. When any single zone temperature reaches a preset point, the entire system is turned back on until all zones are back to the preset temperature. This sequence is continuously repeated (Black 2008).

Compressors: Compressor efficiency can be improved by reducing the difference between suction pressure and discharge pressure (also known as lift) in the refrigeration system. The lift can be reduced by either raising suction pressure or lowering discharge pressure (Wilcox 2004). Compressor loading and unloading characteristics are an important factor to consider when planning compressor efficiency upgrades.

Condensers: Operating condensers more efficiently involves tracking ambient wet-bulb temperature and resetting the discharge pressure set point to use the currently available condenser capacity (Black 2008). Condenser efficiency can be improved by avoiding operating a condenser when pumps are running and fans are not running, and vice versa. Installing VFDs on condenser fans will also work to achieve energy savings along with improving belt wear and pressure control (Wilcox 2004).

Evaporators: Evaporator efficiency can be improved by selecting higher efficiency coils, avoiding direct expansion evaporators in favor of liquid overfeed or flooded evaporators, and using fans with efficient fan blade design. For evaporator coils that frost, choosing evaporator coils with a fin spacing of four fins per inch or less will also improve energy efficiency (Wilcox 2004).

Improving Part-Load Performance: Refrigeration systems are designed to meet peak loads, but, in many cases, spend little time operating at peak loads. Improving refrigeration equipment part-load performance could have a significant impact on reducing facility energy use. Evaporator part-load performance can be improved by cycling fans, using two-speed fans, and installing VFDs on fans. Compressor part-load performance can be improved by limiting part-load operation, using compressors with the most-efficient part-load performance as trim, and allowing other compressors to run efficiently at full capacity. Condenser part-load performance can be improved by using fan controls that utilize VFDs (Wilcox 2004).

Automated Defrost Control: Coil defrosting adds heat to refrigerated spaces and may reduce moisture content of the refrigerated product (Black 2008). Automated on-demand defrost control instead of regularly scheduled defrost could reduce unnecessary defrosting. Such controls reduce energy use of the refrigeration unit by delaying defrost cycles until the performance of the evaporator coil indicates that defrost is needed.

5.2. Demand Response Opportunities

Industrial refrigerated warehouses which have implemented energy efficiency measures are excellent candidates for OpenADR for both technical and managerial reasons. Since energy efficiency measures already address existing opportunities for reducing energy use and demand on a permanent basis, they serve to establish a base for implementing demand response strategies. Control technologies installed for energy efficiency and load management purposes can often be adapted for OpenADR at little additional cost. In addition, facilities that have already achieved success in energy efficiency and load management may also be more receptive to demand response because their ability to realize benefits from managing their energy use has already been demonstrated. In addition, controls installed, particularly for load management, may provide access to the real-time data needed to determine the likely impact of OpenADR.

Demand response strategies modify facility electricity use during utility peak periods in order to enhance system reliability, respond to market conditions and pricing, and improve the utilization of the facility infrastructure. The degree to which demand response strategies can be automated is dependent upon the level of integration of the facility control technologies.

Site electrical loads during peak periods can be reduced by a variety of strategies which can be grouped into two categories: load shedding and load shifting. These strategies could be part of either facility load management program or be performed as part of OpenADR activities. Demand limiting programs involve daily time-of-use energy management techniques that include careful consideration by a facility of any potential to schedule equipment to avoid increasing peak *facility* electricity loads, to "smooth out" the facility's electricity load curve. Load shedding and load shifting strategies, as components of OpenADR programs, are designed to respond to the occasional need to reduce electricity use during times of peak *utility* load- also known as DR events. Load shedding strategies reduce the facility's total electricity load during DR events, and load shifting strategies change the time of electricity demand to off-peak hours. Figure 5 illustrates the difference in load shape when implementing load shedding and load shifting strategies in the cases of both demand limiting and OpenADR. Demand response strategies need to be structured so as to limit a significant demand increase above baseload levels after the demand response period, except when part of a planned shift strategy. Appropriate control strategies should be applied to reduce sharp demand rebounding by staging equipment affected in the demand response measure.

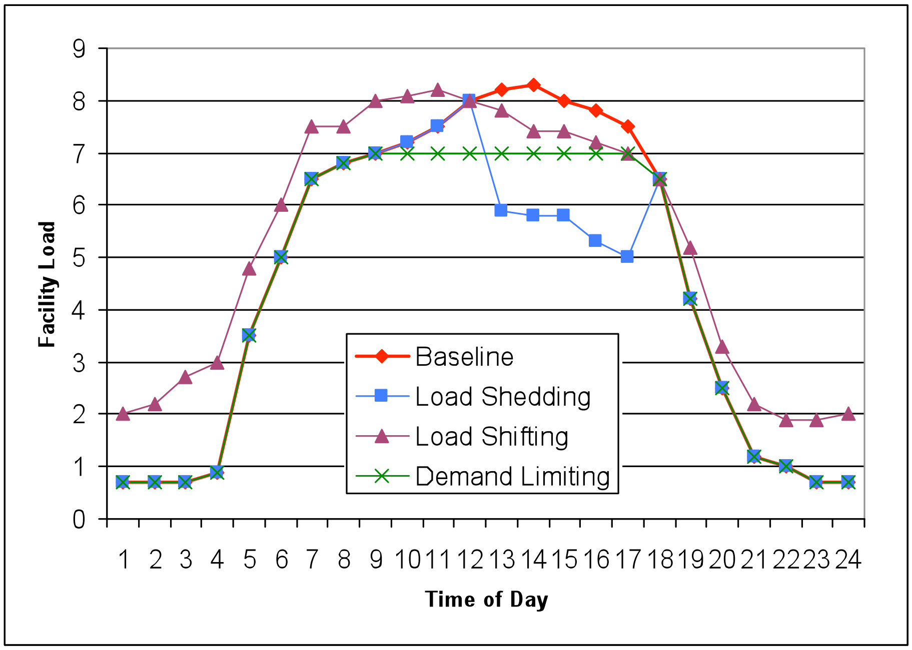

Figure 5. Examples of Load Reduction Strategies[2]

5.2.1. Load Shedding

Load shedding curtails electricity demand during a DR event. Load shedding strategies in industrial refrigerated warehouses include turning off equipment, increasing cold storage area temperature set points, reducing lighting and HVAC loads, and utilizing VFDs to run equipment at lower capacity.

Turning off Equipment: Refrigerated warehouse loads can be reduced by turning equipment such as compressors and condenser and evaporator fans off during demand response events. The magnitude of the load reduction associated with this strategy depends on the refrigerated product's sensitivity, and the level of shell insulation in the refrigerated warehouse.

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[2] This chart is conceptual; the data are not from actual measurements.

Increasing Cold Storage Temperature Set points: Refrigeration loads can be reduced during DR events by increasing the temperature set point in refrigeration units, which, in turn, reduces compressor loads. As in the case of turning off equipment, the magnitude of the set point change depends on product sensitivity and the level of shell insulation in the refrigerated warehouse.

Lighting Shed: Lighting loads in non-essential areas can be shed by turning off or dimming groups of lighting. This results in a reduction in lighting demand and also results in less heat released in the cold storage space, thus reducing the cooling loads. A demand response study of a beer distribution warehouse recommended shedding 50% of refrigerated warehouse lighting, 50–100% of hallway lighting, and 20% of office lighting.

HVAC Shed: Similarly to lighting sheds, the facility HVAC loads can be shed in non-essential areas during DR events by turning off HVAC equipment and increasing temperature set points in office spaces. A demand response study of the U.S. Foodservice warehouse in Livermore, CA found that about 25% of the facility's electrical load could be reduced by turning off HVAC systems. See Section 7, Case Studies, for more details.

Variable Frequency Drives (VFDs): VFDs can be used to reduce equipment electricity demand during DR events and peak hours to run compressors, condensers, and evaporators at the lowest capacity necessary to maintain product quality. California's 2008 Title 24 requires the use of VFDs for all new refrigeration systems (California Energy Commission 2008) – this will reduce facility energy use on a permanent basis, and provide a base for implementing demand response strategies.

5.2.2. Load Shifting

Load shifting moves electricity demand to off-peak hours. Load shifting strategies for industrial refrigerated warehouses include cold storage space pre-cooling, shifting battery charger loads, and disabling electric defrost during demand response events.

Pre-cooling: Pre-cooling reduces refrigerated warehouse space temperatures before a demand response event, allowing refrigeration equipment to be turned off during an event without causing product damage. Pre-cooling effectively charges the product mass and discharges it during demand response events. Though energy demand may increase after the event to compensate for the temperature increase, the increase typically lasts shorter than the duration of the event and occurs during off-peak hours. The ability to successfully pre-cool a warehouse depends on the thermal mass of the product as well as the mass and temperature of any products leaving or being introduced into the storage area. Parameters such as the outdoor temperature and humidity, as well as the temperature losses and temperature fluctuations from entering/exiting the storage areas can have a significant impact. The operation of lighting as well as additional activities in the area (such as forklift operation) also effect pre-cooling strategies.

Pre-cooling strategies, which include choosing time periods for pre-cooling and the magnitude of the temperature set point changes, should be tested to ensure the product is not damaged and to make sure the product itself, not just the ambient air, is pre-cooled to the desired temperature (National Grid 2004). Facilities must also take into account the fact that lowering temperature puts significant additional demand on the refrigerator compressors. Therefore, the refrigeration equipment must be able to withstand the higher refrigeration load during pre-cooling periods (Stoeckle 2001). This strategy has been proven successful in commercial buildings (Xu 2006) and while industrial field tests are limited, it also appears to show significant promise for load shifting in industrial refrigerated warehouses.

Shifting Battery Charger Loads: Battery charging and use can be scheduled so that battery chargers can be shut down during a demand response event. Given prior notice, batteries can be charged before peak hours, and batteries can be rotated so that no battery charging is required during a demand response event (National Grid 2004). Shifting battery charging loads is also used as a daily peak load management strategy. The implementation of this strategy for demand response relates to occasionally rescheduling battery loads that cannot be shifted on a daily basis.

Disabling Electric Defrost: For equipment that utilize electric defrost, automatic evaporator defrosting can be disabled during a demand response event to reduce loads. Evaporator coils can be defrosted prior to a demand response event, so that defrosting will not be needed during the following demand response event (National Grid 2004).

5.2.3. Assessment of California Cold Storage Facilities Ability to Participate in Demand Response Programs

In 2007, Southern California Edison (SCE) surveyed its commercial cold storage customers about their current participation in demand response and load management activities (Southern California Edison 2007). These survey results indicate how other California cold storage facilities will participate in the demand response activities.

Table 5 shows the demand limiting efforts currently undertaken by SCE cold storage facilities to reduce electrical load at times when there is a high demand on the electrical system.

Table 5. Southern California Edison Commercial Cold Storage Customers Current Demand Limiting Efforts

Current Demand Limiting Strategies	Number and Percent of Sites
Turn off lights	8 / 40%
Shut down some process or cooling equipment	4 / 20%
Shift production hours year-round	3 / 15%
Reduce use of some process or cooling equipment	3 / 15%
Run back-up generator	1 / 5%
Other	5 / 25%
Don’t know/Refused	1 / 5%

Source: Southern California Edison. DR Strategies for Cold Storage – Barriers to Implementation. August 2007.

The sites were further surveyed to determine what one-time strategies they would be willing to undertake to reduce electrical load during peak summer operating hours (See Table 6)

Table 6. Southern California Edison Commercial Cold Storage Customers Planned One-Time Demand Response Strategies

Demand Response Strategy	Number and Percentage of Sites
Turn off some lights	30 / 79%
Reduce the frequency of opening doors	26 / 68%
Turn off air conditioning in office space	20 / 53%
Cycle compressors	19 / 50%
Turn off some of the refrigeration/cooling equipment	16 / 42%
Shift production hours	8 / 21%
Switch to back-up generators	4 / 11%

Source: Southern California Edison. DR Strategies for Cold Storage – Barriers to Implementation. August 2007.

The sites which indicated that they would be able to reduce their load by 10% were asked to list the strategies they would take to achieve that reduction (See Table 7).

Table 7. Southern California Edison Commercial Cold Storage Customers Planned Demand Response Strategies to Accomplish 10% Load Reduction

Demand Response Strategy	Number and Percentage of Sites
Turn off some of the refrigeration / cooling equipment	10 / 38%
Keep doors to refrigerated areas or freezers closed / reduce frequency of opening doors	6 / 23%
Turn off lights	5 / 19%
Cycle compressors on large-scale refrigeration	3 / 12%
Turn off air-conditioning in office space	3 / 12%
Delay battery recharging	1 / 4%
Shift production hours	1 / 4%
Other	1 / 4%
Don’t know / refused	4 / 15%

Source: Southern California Edison. DR Strategies for Cold Storage – Barriers to Implementation. August 2007.

5.3. Emerging Demand Response Technologies

Research is currently being conducted on demand response technologies and strategies that have not yet been considered in a wide-range of facilities. An example of these emerging demand response technologies is utilizing wind power as an energy source for refrigerated warehouses operation.

Wind Power and Refrigerated Warehouses: Preliminary research is being conducted on using refrigerated warehouses as a storage medium for wind power produced at night. Currently, a project is being conducted in Dutch refrigerated warehouses by the European Union (EU) and the Sixth EU Framework Program for Research and Technological Development. The project studies storing the electricity produced at night by wind power generators in refrigerated warehouses using the refrigerated products as a storage medium and then releasing that stored energy during hours of peak electrical demand. This strategy was devised to counteract the problems associated with the intermittence of wind energy versus the patterns of electrical demand. Wind power is produced at random hours of the day, whereas electrical demand peaks in the middle of the day and drops at night. By using wind energy when it is available to pre-cool refrigerated warehouse storage areas, electricity demand can be controlled during the peak hours by allowing refrigerated warehouse temperatures to float, thus reducing compressor loads (van der Sluis 2008). The preliminary assessment found that varying warehouse product temperatures by even as little as two degrees Fahrenheit could result in significant electricity savings and demand (Butler 2007).

This project combines existing refrigeration technologies and advanced control strategies. The controls utilize software that tracks the refrigeration equipment load and takes into account demand response or electricity price signals. During low price periods, the refrigerated warehouse is pre-cooled using wind energy. During the high price period or during the peak demand hours, the refrigeration equipment automatically shuts off. The temperature setpoint is determined by demand needs and energy prices and is set by a programmable logic controller, which can be installed as part of an existing refrigeration system (van der Sluis 2008).

6.0 Analysis of Demand Response Studies

Understanding the individual demands in refrigerated warehouses is critical to determining the facility's appropriate demand response actions. LBNL examined data from three submetered food processing facilities and the demand response reductions each achieved during the summer of 2007. LBNL compared the submetered data with total facility demand based on utility data. These facilities were first considered in a 2006 demand response study performed by Quantum Consulting (Quantum Consulting Inc. 2006). Retaining the numbering scheme employed by the Quantum study, Sites 2 and 4 are both agricultural product processing, packing, and cold storage facilities, while Site 3 is a baking and frozen storage facility. LBNL examined a number of end uses in each facility, which were separated into two groups:

- Cold storage demand
- Other submetered end uses (e.g., HVAC, lighting, battery chargers)

6.1. Methodology

Sites 2 and 3 participated in PG&E's Critical Peak Pricing program (CPP) while Site 4 participated in SCE's Demand Bidding Program (DBP). This study evaluated only the event days when the site achieved observable demand reductions during the DR event. Site 2 participated in 11 of the 12 CPP days during the summer of 2007, while Site 3 participated in only 4. Site 4 participated in 16 of the 22 DBP days in the summer of 2007. PG&E's peak period on a CPP event day occurs between 12pm and 6pm, while SCE's peak period on a DBP event day is between 12pm and 8pm.

LBNL compared total facility and end use demand patterns during the peak period of the demand response event on event days against the 3/10 baseline (Coughlin 2008). The 3/10 baseline is derived by averaging the three days with the highest demand out of the previous ten days, excluding weekends, holidays, or other demand response event days.

6.2. Data

Figures 6 through 17 show examples of the event day demand and calculated baseline demand on a representative event day, August 28th, 2007 for Sites 2 and 4, and July 6th, 2007 for Site 3. The first figure shown for each site depicts the total and submetered demands on the event day (Figures 6, 10, and 14). The following figures separate the total (Figures 7, 11, and 15), cold storage (Figures 8, 12, and 16), and other end use (Figures 9, 13, and 17) demand compared with the 3/10 baseline for each site.

The demand reduction results are different for each of the three sites. The cold storage demand reduction can be seen during the demand response event for Site 2, in Figure 8. No discernible demand reductions are apparent for Site 3. Demand reductions accomplished by end uses other than cold storage can be seen during the demand response event for Site 4 (Figure 17).

6.2.1. Site 2

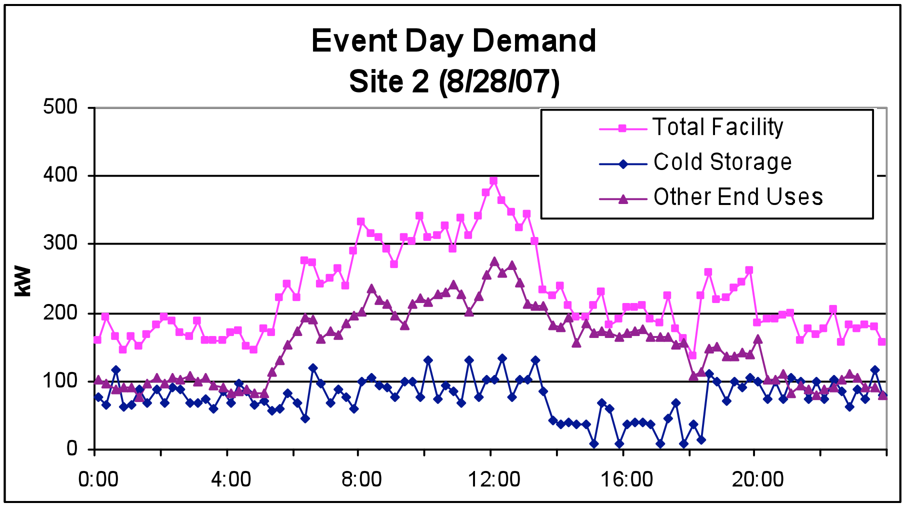

Figure 6. Site 2 - Event Day Demand

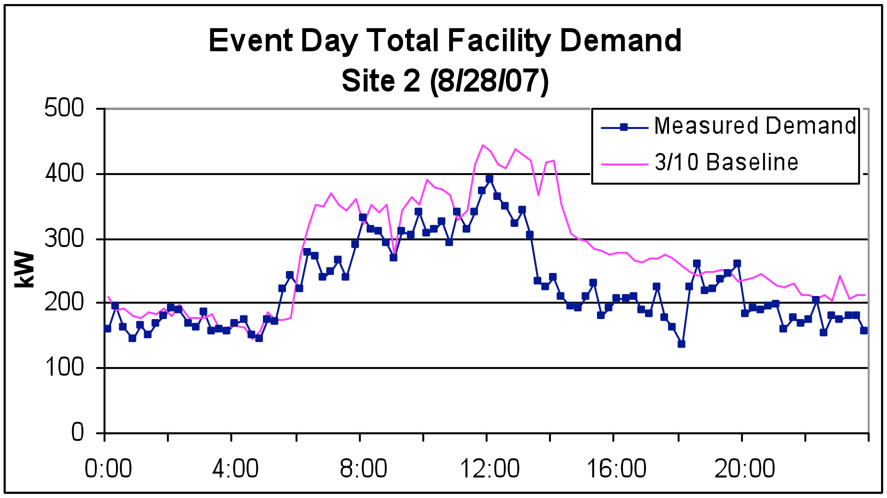

Figure 7. Site 2 – Event Day Total Facility Demand

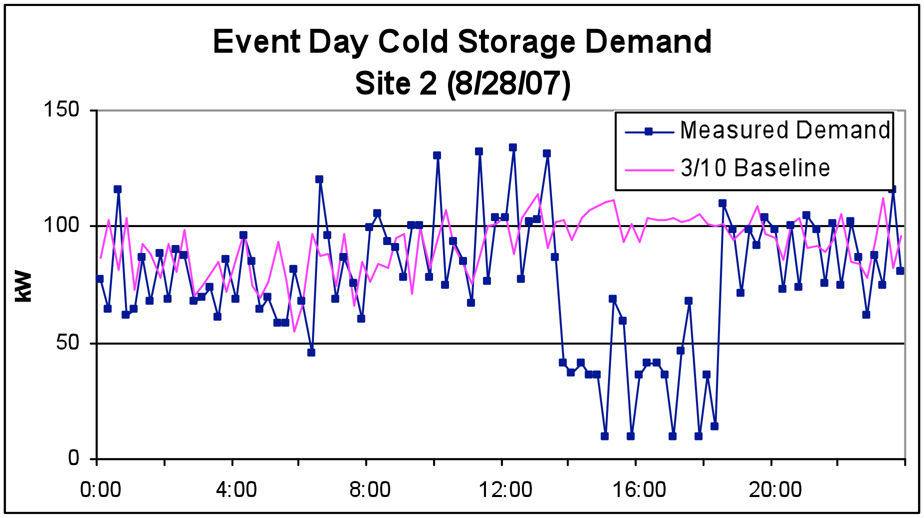

Figure 8. Site 2 – Event Day Cold Storage Demand

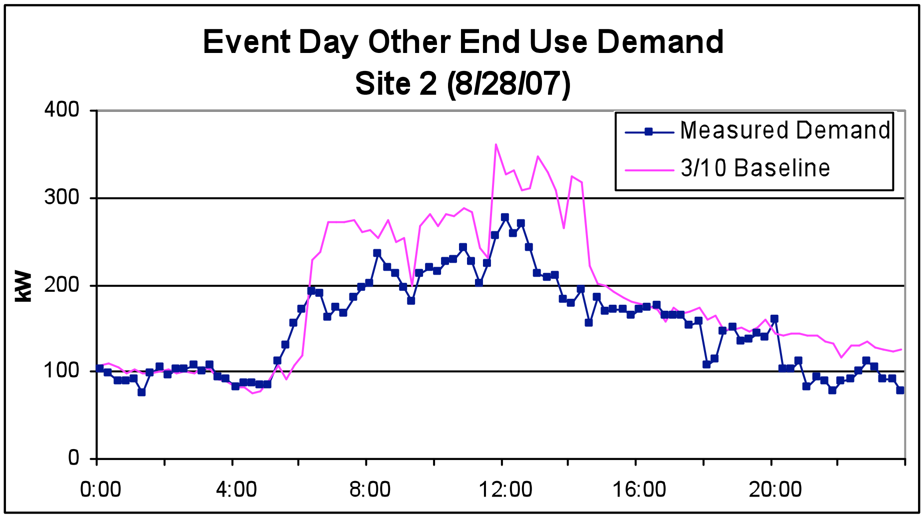

Figure 9. Site 2 – Event Day Other End Use Demand

6.2.2. Site 3

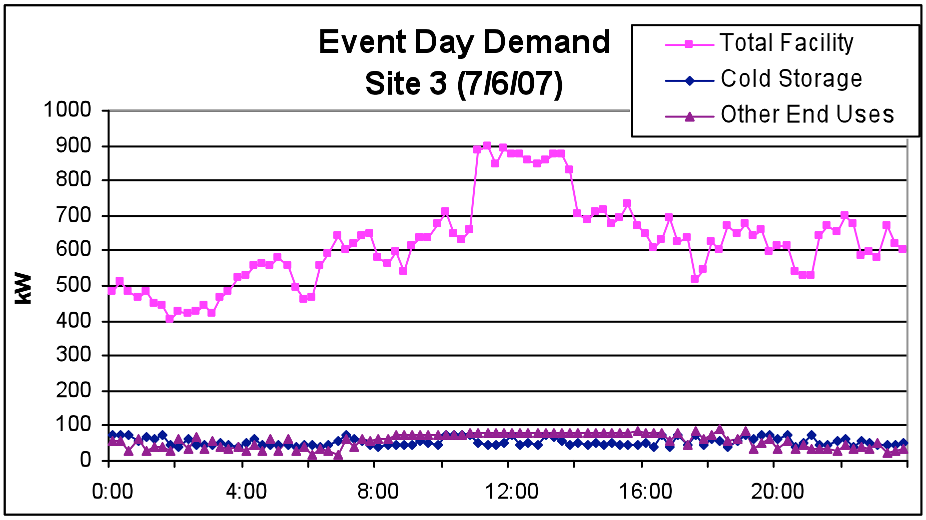

Figure 10. Site 3 - Event Day Demand

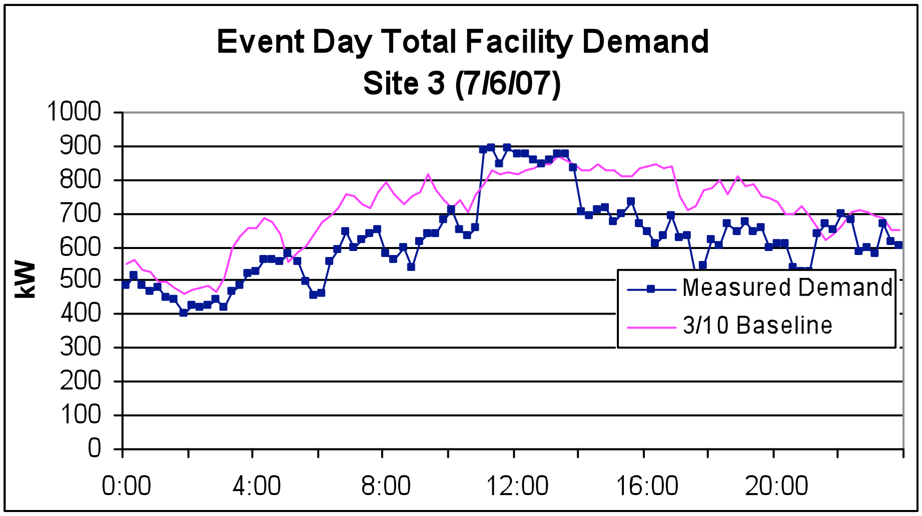

Figure 11. Site 3 - Event Day Total Facility Demand

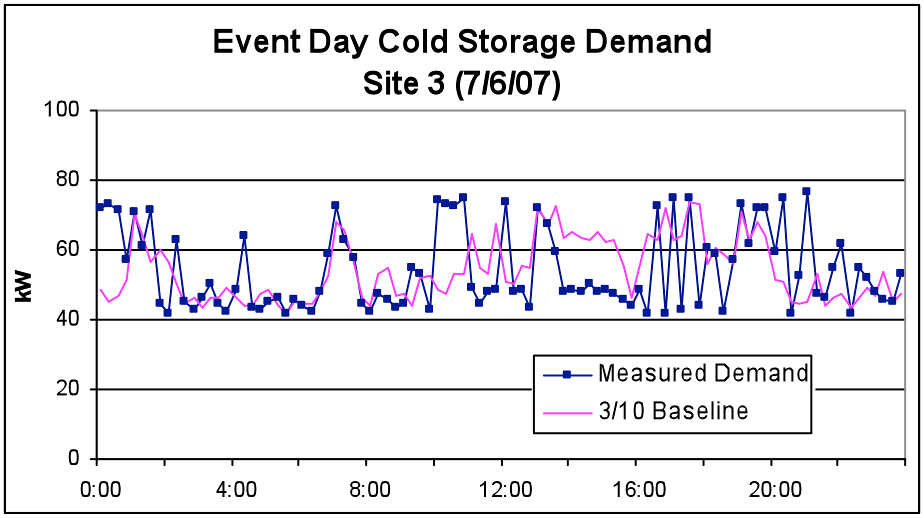

Figure 12. Site 3 – Event Day Cold Storage Demand

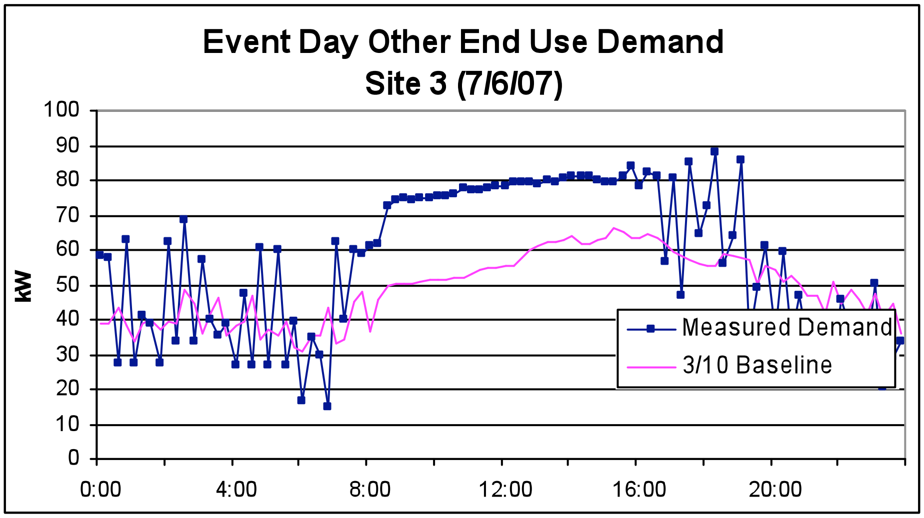

Figure 13. Site 3 – Event Day Other End Use Demand

6.2.3. Site 4

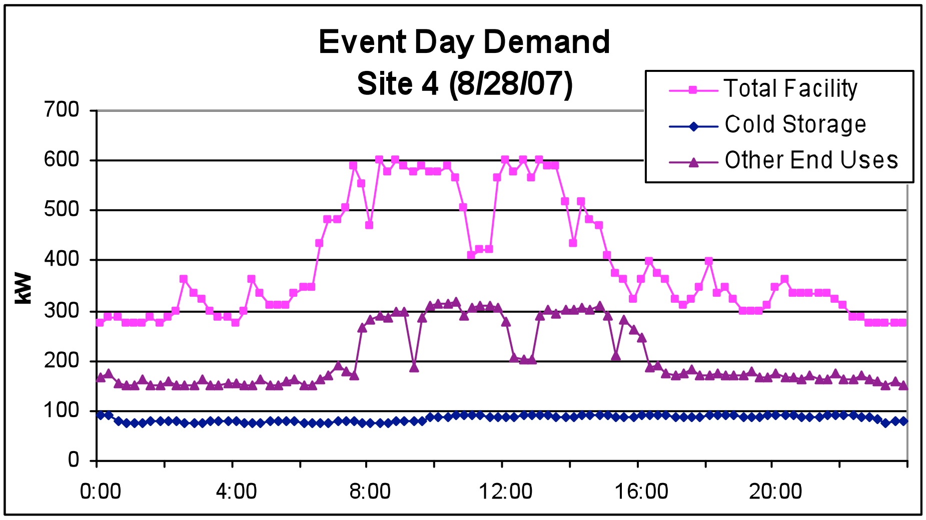

Figure 14. Site 4 - Event Day Demand

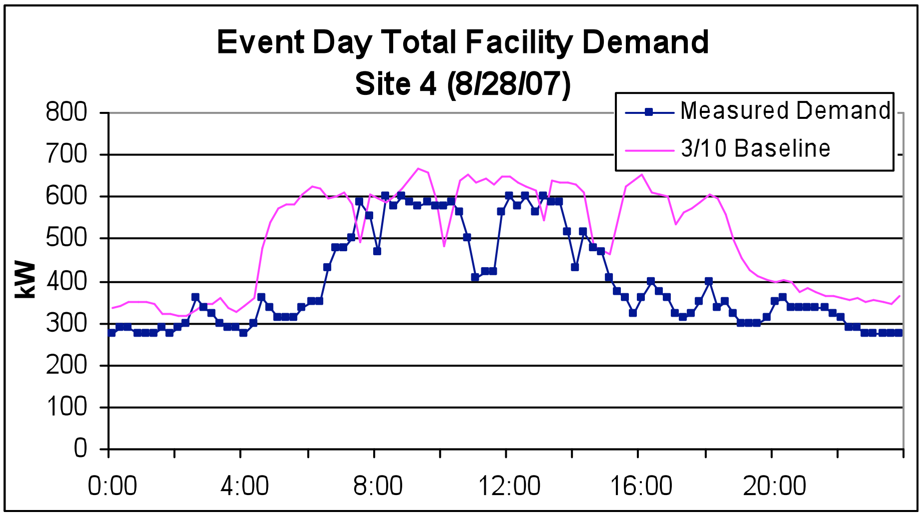

Figure 15. Site 4 - Event Day Total Facility Demand

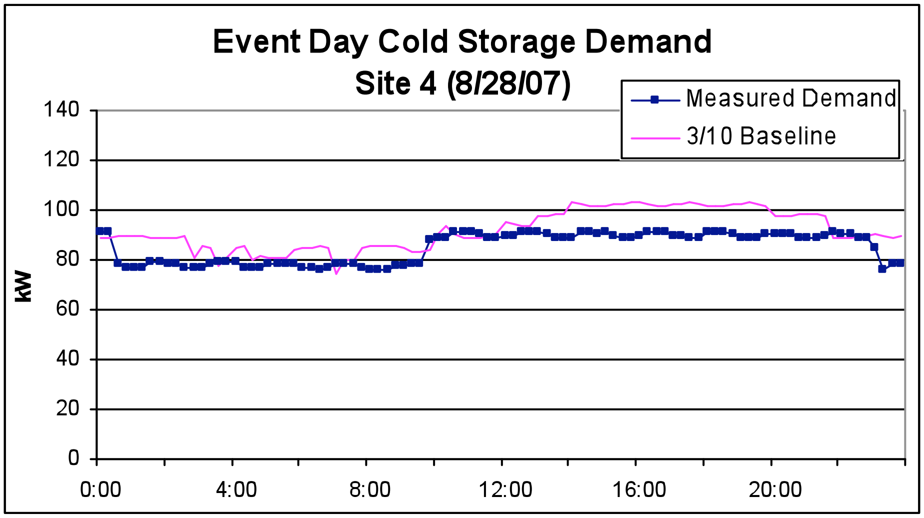

Figure 16. Site 4 - Event Day Cold Storage Demand

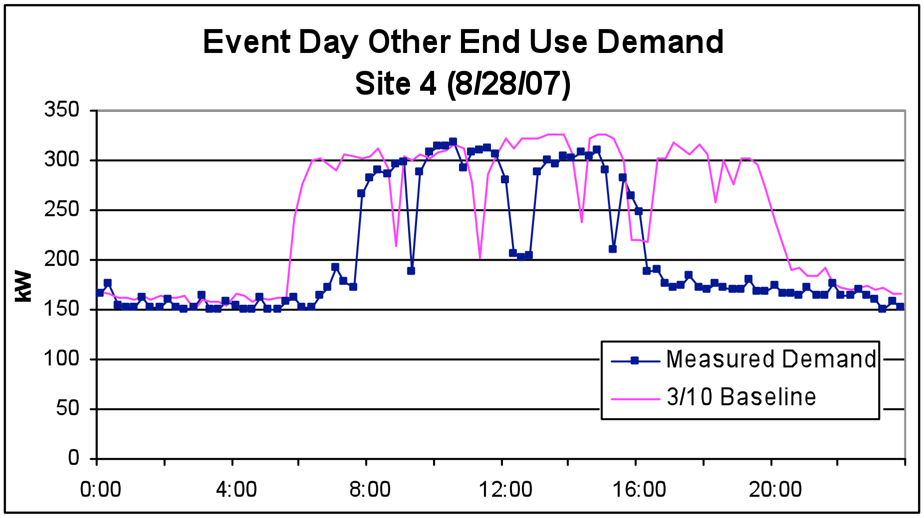

Figure 17. Site 4 – Event Day Other End Use Demand

6.3. Analysis Results

Table 8 shows the average demand for the three sites during the peak period of the event days each participated in during the summer of 2007. The measured demand is shown along with the 3/10 baseline for the total facility load for each site. To determine the statistical uncertainty of the demand reduction during demand response events, the standard error of the 3/10 baseline was determined. The standard error was either added or subtracted from the average 3/10 baseline to establish low and high values for a range for the 3/10 baseline. The load shed for each site is presented along with the percent load reduction accomplished for the low, average, and high baseline range.

The average load shed for Site 2 was 28%, ranging from 24 to 32% and resulting mainly from cold storage reductions. The average load reduction for Site 3 was 18%, ranging from 16 to 20% and did not result from a specific submetered end use. The average load shed for Site 4 was 21%, ranging from 18 to 24% and resulting mainly from submetered end uses other than cold storage.

Table 8. Average Total Facility Peak Period Load Shed

	Site 2			Site 3			Site 4		
	Total Demand	Total Demand Reduction		Total Demand	Total Demand Reduction		Total Demand	Total Demand Reduction	
	kW	kW	%	kW	kW	%	kW	kW	%
Measured Demand	210	-	-	670	-	-	430	-	-
3/10 Baseline – low	275	65	24%	799	130	16%	523	94	18%
3/10 Baseline – average	291	81	28%	818	148	18%	544	114	21%
3/10 Baseline – high	308	97	32%	837	167	20%	565	135	24%

Figure 18 through Figure 20 graphically represent the demand reduction results from each end use for each site. The total and submetered demand and the 3/10 baseline is shown for each site.

Site 2: Figure 18 shows that Site 2 achieved a majority of its demand reduction from cold storage. When compared to the 3/10 baseline during event day peak periods, total facility demand decreased from an average of 291 kW to 210 kW, or 28%. Site 2 achieved these load reductions by turning off compressors and letting the refrigerated warehouse temperature drift. The average temperature drift during the demand response events was 8°F.

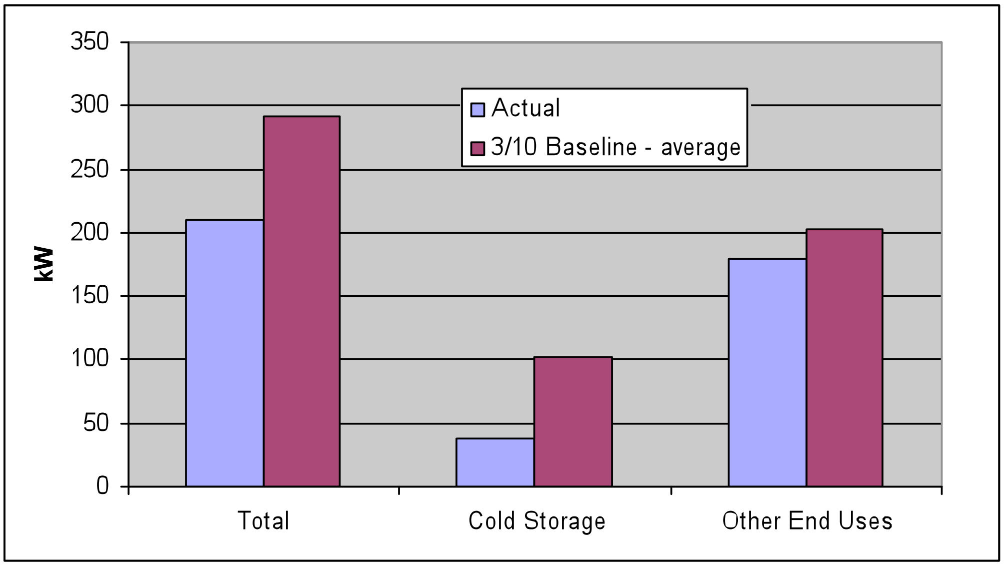

Figure 18. Site 2 Peak Period Demand

Site 3: Figure 19 shows that Site 3 achieved the majority of its demand reduction from loads that were not submetered, however, the available information does not indicate if all cold storage end uses were submetered. When compared to the 3/10 baseline during event day peak periods, total facility demand decreased from an average of 818 kW to 670 kW, or 18%. Site 3 planned on turning off HVAC chillers to reduce cold storage loads, and to turn off additional process loads such as battery chargers.

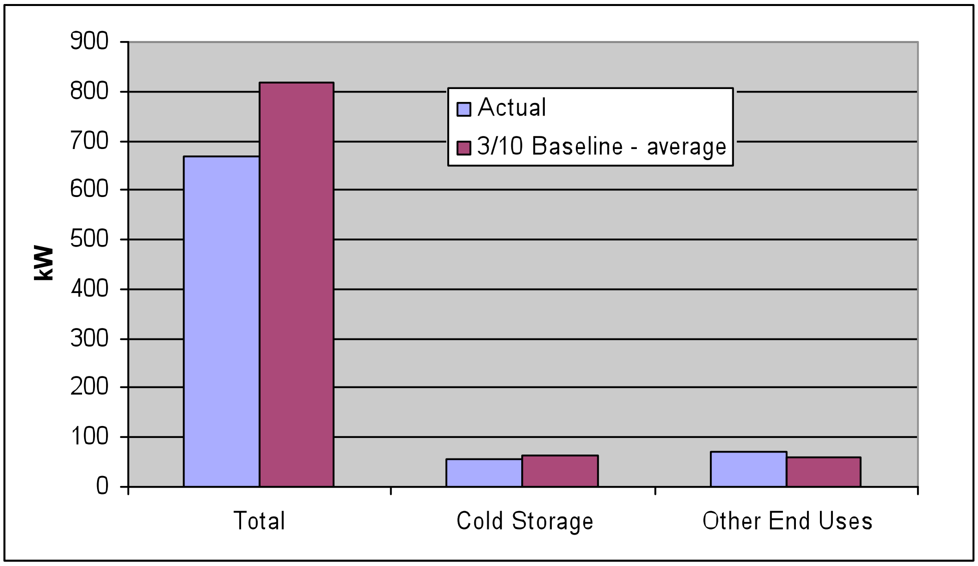

Figure 19. Site 3 Peak Period Demand

Site 4: Figure 20 shows that Site 4 achieved demand reductions from end uses other than cold storage. Compared to the 3/10 baseline during participating event day peak periods other end use demand was reduced from 544 kW to 430 kW, or 21%. Site 4 achieved these other end use load reductions through curtailing site processes and shutting off various building loads.

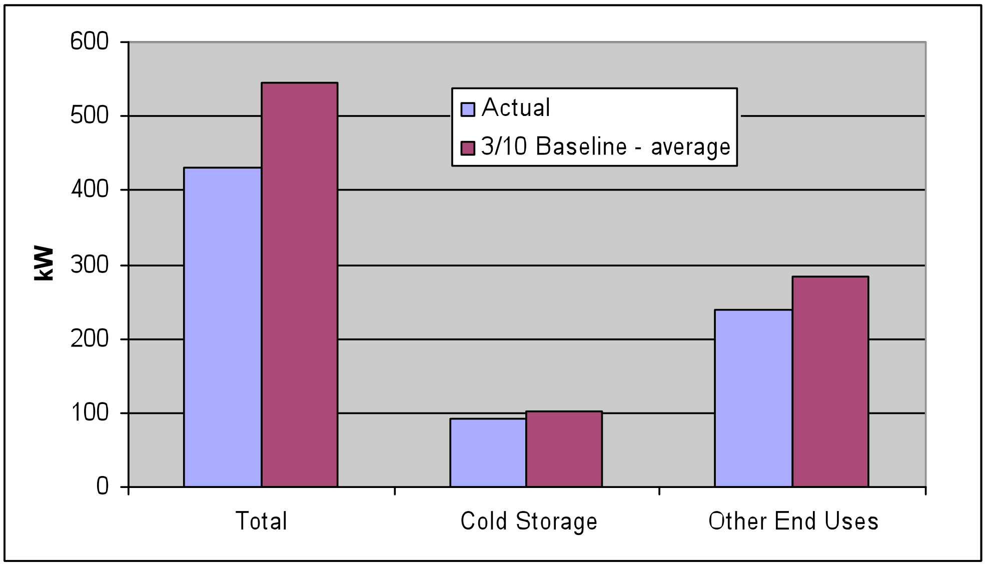

Figure 20. Site 4 Peak Period Demand

In order to determine if any of the measured end use loads varied with temperature, the data were analyzed for weather sensitivity and load variability. The data were rank ordered according to the end use load and temperature, and correlation coefficients were generated. Table 9 below shows the correlation coefficients values for each end use evaluated in each site for the entire summer periods that include the event days.

Table 9. Outdoor Temperature versus Load Correlation Coefficients

Load Type	Site 2	Site 3	Site 4
Total	0.264	0.219	-0.082
Refrigerated Warehouse	-0.009	0.362	0.436
Other End Uses	0.362	0.445	0.215

Correlation coefficients below 0.700 indicate no outdoor temperature dependence. Therefore, the data reported in Table 8 show no correlation between the loads and outdoor temperature for these sites.

7.0 Case Studies

The effectiveness of energy-efficiency retrofits and demand response strategies in reducing facility energy use and demand can be illustrated by examining case studies of successful energy efficiency and demand response implementations in industrial refrigerated warehouses. This section presents 11 case studies that describe facilities ranging from a 5,600 square meter (60,000 square foot) winery to a 42,000 square meter (450,000 square foot) refrigerated warehouse facility. Five of the case studies describe examples of demand response activities, such as shutting off cold storage units, lighting and HVAC systems. In one of the facilities, the set of demand response measures resulted in demand savings of over 200 kW (about 25%). The rest of the case studies focus on energy efficiency measures such as installing more efficient equipment and increasing envelope insulation. In one of the facilities, the set of energy efficiency measures resulted in annual energy savings of over 1.9 million kWh, which accounted for a 34% of the facility's baseline energy use.

7.1. U.S Foodservice

The U.S. Foodservice distribution warehouse in Livermore, California stores more than 10,000 products and includes a 32,000 square meter (345,000 square foot) freezer, which maintains temperatures between -18° to -17°C (-1° to 1°F) (Demand Response Research Center 2009). The entire facility has a typical electrical load of 700–900 kW, with the freezer accounting for 30–40% of the total load.

The facility applied several energy efficient measures including installing high efficiency lighting, installing motion sensors on all lighting, and installing occupancy sensors in all offices and conference rooms. The facility was also an excellent candidate for OpenADR participation due to the freezer and HVAC system's stable electrical load. Additionally, the site had already installed the controls and communication structure necessary to implement OpenADR.

The facility conducted several test DR events in the spring of 2008, in which the air handlers units serving the freezer were turned off, the temperature setpoint of the HVAC system was raised, and battery chargers were turned off. These strategies enabled the facility to shed about 25% of its total load, and had a maximum load reduction of 330 kW. Turning off the freezer air handlers achieved the largest demand reduction. After a six-hour test event, the air temperature near the doors of the freezer had risen by 8.6°F, and the air temperature of the far walls of the freezer rose 1.2°F, with the temperatures of the product remaining within acceptable limits, and without impacting facility operations.

7.2. Agricultural Product Processing Facilities

A study of demand response strategies in two agricultural product processing facilities was conducted in 2004 by Quantum Consulting (labeled sites 2 and 4 in report) (Quantum Consulting Inc. 2006). These facilities are agricultural product processing, packing and cold storage facilities, which use cold storage processes extensively. Neither facility has a written demand response plan. In both cases, cold storage loads were curtailed manually rather than automatically. Additionally, because of the nature of these facilities' products, work, and production schedule are highly variable. Potential bill savings and good corporate citizenship motivated these sites to participate more than utility incentives.

Both sites' main electricity end-use was cold storage and the primary demand response strategy was to manually turn off compressors, letting the product core temperatures float.

Site 2 originally planned to manually shut off 20% to 30% of their total loads by turning off cold storage systems for up to 6 hours in three buildings. This process was not anticipated to damage stored fruit products as long as temperatures did not exceed 60ºF for more than one day. Selected process and packing lines as well as some lighting loads could be shut off during hours of low activity or slightly before the facility closes.

The submetered data from three event days, each consisting of one 6 hour demand response event, shows that the average cold storage reduction for Site 2 accounted for 65% of the average total reduction from those three event days, and only resulted in a temperature drift of 8˚F. The reduction potential may be higher because a back-up generator was installed during the study to reduce summer loads, which lowered daily peak loads, diminishing curtailment potential.

Site 4 originally planned cold storage and process curtailments and predicted potential curtailments of 650 kW. Some of the process curtailments could be shut off for up to 6 hours. The facility initially felt maintaining this level of curtailment would be impossible for more than a two-hour period because of one product's temperature sensitivity. However, a second type of agricultural product in a separate cold storage unit could withstand greater temperature increases, as high as 3 degrees, without experiencing spoilage. In both cases it is assumed that rising cold storage temperatures could not be sustained for the full six hours.

Minimizing testing and service impacts allowed up to 8 hours of load shedding for Site 4. Site 4 also shifted daytime loads to smaller chillers which diminished curtailment potential. Site 4's data from three event days, each consisting of one 8 hour event, shows that the average cold storage reduction accounted for 16% of the average total reduction from those 3 event days, using the 10-day adjusted baseline. The majority of the curtailments were from HVAC and process equipment.

In both sites, after turning off compressors, the agricultural products were monitored for tolerance levels to temperature changes since managers were concerned about product damage. Production managers were also cautious about curtailing process loads because their production schedules are typically difficult and time-consuming to rearrange. During the course of this study, both sites refined their demand response strategies to include more pre-cooling, pre-curtailment, and subload shedding, however, the report does not quantify the impacts of these refinements.

Both sites found that manual cold-storage curtailment was a consistent and manageable reduction method for longer demand response events. Cold-storage curtailments were found to be more effective than curtailing numerous process loads. Processing loads were found to be good load reducers (especially in the peak season) but this was abandoned as a potential demand response strategy because of the costs and difficulties with altering process schedules. Both sites became increasingly involved with demand response strategies as is evident in their plan refinement.

7.3. Bakery

A study of demand response actions in a baking and frozen storage facility was conducted in 2004 by Quantum Consulting (labeled site 3) (Quantum Consulting Inc. 2006). The facility's main electricity end-uses are manually-controlled cold storage, HVAC, lighting, and process equipment. The operators indicated that their motivation for participating was to avoid blackouts and good corporate citizenship rather than bill savings (More detailed information in the summary table in Appendix B).

The primary demand response strategy was cold storage reduction by turning off HVAC chillers (also used for food preservation) and cold storage compressors, as well as additional process loads such as mixers and battery chargers. Four additional chillers in the cold storage warehouse could have been curtailed for up to 24 hours as well. The facility also indicated the possibility of shutting down a production line or an extra mixer during a peak event. Possible curtailments of at least 200 kW were estimated.

The facility curtailed chillers and cold storage loads, and also curtailed lighting, by using only skylight daylighting especially during brighter seasons (because the CPP program emphasizes daily peak load reduction). Additionally, Site 3 was in a moderate climate which diminished the potential for HVAC load reduction. However, during actual demand response events the facility did not curtail the full range of electrical loads presented.

As a whole, the facility did not achieve significant load reductions. However, the data from three event days, each consisting of one 6 hour event, show that the average cold storage reduction accounted for 33% of the average total reduction from those three event days, using the 10-day adjusted baseline.

7.4. Beer Distribution Warehouse

A study of a beer distribution warehouse in Rhode Island was conducted to determine demand response opportunities within the facility in 2003 (National Grid 2004). The study found that the facility had a peak energy demand of 463 kW, with refrigeration contributing over half the facility load. The study examined the facility's peak hours of electricity demand, and found that more than half of the top 50 peak hours occur on weekdays between 12pm and 5pm. The facility peak loads occur during the summer months, but the study found that the influence of outdoor temperature on the facility's energy usage was insignificant. The study determined energy efficiency opportunities within the facility as well as potential demand response strategies. These strategies were described as either load shedding or load shifting opportunities for the warehouse.

Load shedding opportunities included lighting and HVAC sheds throughout the facility. The study recommended shedding 50% of refrigerated warehouse lighting, 50–100% of hallway lighting, and 20% of office lighting. The lighting shed was estimated to reduce demand by 32 kW. The study also recommended reducing the facility HVAC load by raising temperature set points in non-essential areas. This strategy was estimated to shed 20% of the office cooling load and save 17 kW.

Load shifting opportunities included battery-charging, the refrigerated warehouse cooling load, and the evaporator electric defrost. For battery charging, the study recommended that the facility precharge the batteries before a demand response event, and schedule battery use so that all charging stations could be shut down during the demand response event. This strategy was expected to affect 50% of the facility's battery-charging load and save 16 kW. Another load shifting strategy was to pre-cool the refrigerated warehouse in order to shut down all compressors during the demand response event. This strategy was estimated to save 74 kW of refrigeration load. The study also recommended disabling electrical defrost in refrigerated warehouse units during the demand response event. This was estimated to provide a demand savings of 20 kW. Table 10 summarizes the load reduction estimated for each demand response strategy.

Table 10. Summary of Demand Response Strategies in a Beer-Distribution Warehouse

Demand Response Strategy	Shift / Shed	Load Reduction (kW)
Lighting Shed	Shed	32
HVAC Shed	Shed	17
Charging Batteries in Off-peak hours	Shift	16
Pre-cool Refrigeration Unit	Shift	74
Disabling Electric Defrost during Demand Response Event	Shift	20
Total		**159**

The application of these demand savings measures was predicted to save the facility $2,802 in 2003. These savings include energy bill savings, reduced demand charges, and utility incentives.

7.5. Stamoules Produce

Stamoules Produce 5,600 square meter (60,000 square foot) cold storage facility in Mendota, California installed an advanced computer control system coupled with variable speed drives on condenser and cooling fans which was estimated to increase the refrigeration system's efficiency by 25% (Pacific Gas and Electric Company). These upgrades were estimated to save 937,535 kWh and $93,000 per year.

7.6. Fetzer Vineyards

Fetzer Vineyards is a wine producer which operates a facility in Hopland, California and a second winery in Paso Robles, California (Flex Your Power 2008). The Hopland facility includes a 930 square meters (10,000 square foot) administration building, and the Paso Robles winery totals 25,000 square meters (270,000 square feet). Both buildings utilize energy efficient building construction.

Fetzer Vineyards applied several energy efficient measures to improve its refrigeration system, which comprises the majority of their electricity usage. Fetzer installed part load controllers (PLCs) on a total of 1200 hp of compressor motors to control refrigerant temperature, pressure, and compressor cycles. This upgrade resulted in annual energy savings of about 225,000 kWh and cost savings of about $30,000. They also installed electrodialysis equipment for white wine production instead of the more energy intensive cold stabilization method of tartrate removal, which requires sustained temperatures of -3.3°C (26°F) for two to four weeks.

7.7. J Vineyards and Winery

J Vineyards and Winery is a 5,600 square meters (60,000 square foot) facility located in the Russian River Valley in Sonoma, California (Flex Your Power 2008). The cold storage facility maintains between 13–16°C (55–60°F) year round. Refrigeration is estimated to account for more than 70% of their energy usage.

J Vineyards and Winery invested in energy-efficiency retrofits in 2000. It installed a more efficient refrigeration unit, and increased insulation by layering three inches of foam between concrete walls. The insulation increase resulted in refrigeration demand savings that saved the company $71,000. Computer controls were also installed to control variable-speed compressors to track or match the refrigeration load. The facility also retrofitted its lighting and reduced their lighting load by more than 50%.

7.8. S. Martinelli and Company

S Martinelli and Company operates a 42,000 square meters (450,000 square foot) facility in Watsonville, California (Flex Your Power 2008). In 2005, the facility applied energy efficiency measures that included retrofitting highbay fixtures with fluorescent lamps and electronic ballasts, installed skylights to minimize dependence on electric light and installed motion sensors in unoccupied areas. Additionally, they increased the insulation on steam lines used in the pasteurization process which allowed for shorter operation times and also reduced heat losses. These retrofits reduced annual energy use by 13% in 2005, saving the facility over 700,000 kWh annually.

S. Martinelli and Company took measures to implement demand response strategies in the facility. They installed a computer control system that is capable of curtailing peak loads by managing compressors, lighting and HVAC systems. The facility participates in PG&E's voluntary demand bidding program. During demand response events, workers were tasked with maintenance jobs while operations were halted or slowed to save energy. The company reduced as much as 50 kilowatts of demand per demand response event.

7.9. Henningsen Cold Storage

Henningsen Cold Storage built a refrigerated warehouse in Gresham, Oregon in 1996 (Wilcox 2004). The 4,600 square meters (50,000 square foot) refrigerated warehouse was designed to include efficient equipment, controls, extra insulation and energy-efficient lighting.

The energy-efficiency improvements made to the warehouse included shell measures (0.5 meter [six inch] thick extruded polystyrene wall insulation, 0.15 meter [six inch] extruded polystyrene floor insulation, 0.38 meter [15 inch] extruded polystyrene ceiling insulation), three fast-acting doors serving the loading dock, lighting retrofits, an oversized condenser, axial condenser fans, VFDs for condenser and evaporator fan controls, evaporators sized for a 10°F temperature difference, three different sized screw compressors, thermosiphon compressor cooling, premium-efficiency motors, a central control system, an automatic non-condensable gas purger and VFD and slide-valve control on one of the compressors.

These upgrades in equipment and controls cost $410,000, which was partially offset by utility incentives and state business energy tax credits. When compared to a baseline refrigerated warehouse with a standard design and standard equipment and controls, the improvements made to the Henningsen Cold Storage Warehouse provided a 42% reduction in annual energy use, resulting in an energy savings of 1,140,000 kWh each year. Two years after it was built, Henningsen Cold Storage doubled the size of its facility, and again installed efficient design, equipment and controls. This provided an additional energy savings of 660,000 kWh per year. These significant energy efficiency improvements successfully demonstrated options that could be applied as demand response strategies.

7.10. Oregon Freeze Dry

The Oregon Freeze Dry facility in Albany, Oregon is the largest custom processor of freeze-dried products in the world and is specialized in freeze-drying processes (Wilcox 2004). The facility has three energy-intensive manufacturing areas which utilize a two-stage ammonia refrigeration system that serves 14 freeze-dry spaces and several cold storage spaces.

Oregon Freeze Dry performed a study to investigate energy efficiency improvements in the facility. The study determined that the existing compressors inefficiently varied capacity with slide valves, and installing VFDs would allow the compressors to operate at different speed depending on refrigeration loads. As a result, VFDs were installed on four screw compressors. In addition, the refrigeration system was improved by replacing an undersized 0.2 meter (8-inch) suction line with a 0.3 meter (12-inch) line. The 0.3 meter (12-inch) suction line created a smaller pressure drop which reduced system suction pressure losses. Also, central controls were enhanced to manage the VFDs and determine what speeds to run the compressors at to meet the refrigeration loads at optimum efficiency.

These energy efficiency retrofits cost the facility $241,777, which was partially offset by state business energy tax credits and utility incentives. These upgrades resulted in energy savings of 1,939,000 kWh annually, a 34% reduction from the facility's baseline use and a demand savings of 160 kW. Additionally, these retrofits reduced maintenance costs by decreasing wear on motors and compressors due to soft starts and fewer operating hours. Some of the energy efficiency measures could also be applied as a part of demand response strategies.

7.11. WestFarm Foods

WestFarm Foods is a dairy manufacturer which initiated a modernization of their dairy plant in Portland, Oregon in 1996 (Wilcox 2004). WestFarm Foods performed a comprehensive energy study which included data logging of the existing refrigeration system to record suction pressure, condensing pressure, compressor slide valve positions, run time for the liquid solenoid valves, and compressor power.

This data logging revealed that the compressors were operated unloaded much of the time, because they were sequenced manually, not using automated control. Additionally, the high minimum condensing pressure resulted in increased compressor power and the evaporator coil liquid solenoids in the milk cooler were off some of the time, which resulted in excessive use of fan power.

As a result of these findings, several energy efficiency retrofits were applied to the facility, including installing a computerized control system to improve compressor sequencing, and better control of condenser fan set points. A 260 kW (350-hp) VFD was installed on the compressor, which originally utilized slide valves to provide load trim. VFDs were also installed on several evaporator fans in the facility. The computerized control system reduced fan speed when space temperature requirements were satisfied. A new high-pressure ammonia receiver with a booster pump was installed to ensure adequate liquid pressure. This allowed the minimum condensing pressure to be reduced. All condenser fans were equipped with VFD controls to manage condenser capacity by adjusting speed rather than cycling.

The implemented measures reduced annual energy consumption by 2,000,000 kWh, accounting for 40% of the total refrigeration energy use. It resulted in an annual operating cost reduction of $75,000. These energy-efficient improvements cost the facility $310,000, which was partially offset by utility incentives and state government tax credits. The incentives and tax credits brought the initial 4.2-year payback down to one year.

8.0 Conclusion

This study has shown the refrigerated warehouses can be excellent candidates for demand response. Facilities which have implemented energy efficiency measures and have centralized control systems may be able to shift or shed process loads in response to financial incentives, utility bill savings, and/or opportunities to enhance reliability of service. Control technologies installed for energy efficiency and load management purposes can often be adapted for OpenADR at little additional cost. These improved controls may prepare facilities to be more receptive to OpenADR due to both increased confidence in the opportunities for controlling energy cost/use and access to real-time data.

Conversely, OpenADR affords industrial facilities the opportunity to develop the supporting control structure and to "demo" potential reductions in energy use that can later be applied to either more effective load management or a permanent energy use reduction via energy efficiency. Energy efficiency, load management, and OpenADR are highly compatible activities for refrigerated warehouses.

This study also found that opportunities for demand response depend on how efficiently refrigerated warehouses are constructed, Higher shell thermal integrity creates a better base for demand response results. Facilities' demand response strategies must account for product characteristics, in particular the range of temperatures sensitivities of the specific product.

Within refrigerated warehouses, the main energy end-uses are product refrigeration and processes, lighting, maintaining water temperatures, HVAC, manufacturing processes and charging forklift batteries. Refrigeration and electrical defrost can account for over two-thirds of the demand. Electrical loads vary depending on the facility and the season.

The equipment that enable successful demand response strategies include advanced compressors, intelligent defrost control as well as condensers and evaporator fan controls. The individual equipment is controlled via a system of sensors and actuators, which often communicate with the facility central system. Although limited, preliminary field data shows that distributed control systems are currently the prevalent type of control in refrigerated warehouses in California. However, supervisory control systems are most suitable for integration into automated demand response architecture and allow for effective coordination of load shed and shift activities during demand response events.

The study identified multiple energy efficiency and automated demand response opportunities in refrigerated warehouses. Energy efficiency opportunities include installing increased shell insulation, efficient equipment and lighting HVAC retrofits, and better matching of equipment to load. Load shedding curtails electricity demand during a demand response event. Load shedding strategies in industrial refrigerated warehouses include turning off equipment, increasing cold storage temperature set points, reducing lighting and HVAC loads, and utilizing VFDs to run equipment at lower capacity. Load shifting strategies for industrial refrigerated warehouses include cold storage space pre-cooling, shifting battery charger loads, and disabling electric defrost during demand response events.

The effectiveness of energy-efficiency retrofits and demand response strategies in reducing facility energy use and demand was illustrated by examining case studies of industrial refrigerated warehouses. The examples clearly showed that many of the considered energy efficiency technologies could be utilized for automated demand response.

The analysis of the three refrigerated warehouses showed significant demand reduction potential in both cold storage and other end uses. Although the data from these three sites is not sufficient to derive definitive conclusions about which end uses are most suitable to participate in demand response events, it appears that the cold storage end use has the highest potential, but some facilities could get significant additional load reductions from other end uses such as HVAC systems or battery chargers. One analyzed facility was able to reduce its load by 29% with cold storage reductions. Another site was able to reduce its load by 26% by reducing other end use demand. Additional analysis based on these limited data indicated that was no correlation between this sample of refrigerated warehouses loads and outdoor temperature.

The research and conclusions reached in this report offer insights to help shape the path of further demand response and refrigerated warehouses research. This research might include: the development of more advanced DR-enabling control technologies and systems, improving refrigerated warehouse construction to enable energy efficiency, or collecting data from more demand response events and analyzing the data to determine effective strategies. Collecting data and performing analyses to address the issue of stock turnover rate for equipment such as compressors, fans, and controls could help further target opportunities for introducing energy efficiency and demand response-enabled equipment. At the facility level, field study of additional facilities beyond the limited number available for this report could help determine which loads to shed, how to use existing technologies to plan demand response events and energy efficiency, which technologies need to be upgraded to enable activities, and how to interact with utilities to ensure benefits and support for participation.

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10.0 Glossary

ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
ADR	Automated Demand Response
CEC	California Energy Commission
CPP	Critical Peak Pricing
DBP	Demand Bidding Program
DCS	Distributed Control System
DR	Demand Response
DRRC	Demand Response Research Center
EU	European Union
GWh	Gigawatt Hour
HMI	Human Machine Interface
HVAC	Heating, Venting, and Air-Conditioning
I/O	Input/Output
ISO	Independent System Operator
kW	Kilowatt
LBNL	Lawrence Berkeley National Laboratory
LCD	Liquid Crystal Display
MW	Megawatt
OAT	Outdoor Air Temperature
OpenADR	Open Automated Demand Response
PIER	Public Interest Energy Research
PG&E	Pacific Gas & Electric Company
PID	Proportional Integral Derivatives
PLC	Programmable Logic Controller
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SDG&E	San Diego Gas and Electric
USDA	United States Department of Agriculture
VFD	Variable Frequency Drive

Appendix A: Refrigerated Warehouse Technologies

The following series of tables provide specific information on the different components of a refrigerated warehouse, their purposes and control. The following tables summarize information from Wilcox (Wilcox 2004) and ASHRAE (ASHRAE 2008).

Table 11. Evaporator Technologies

EVAPORATORS – fans blow warm air over cold liquid refrigerant, cools air, boils refrigerant to vapor	
Refrigerant-to-air coils – type of evaporator, most common – cooled refrigerant passes through tubes via recirculated, overfeed, flooded or direct expansion systems – axial (most common) fans or centrifugal fans move air through coil	**Fan controls** – can be used to control evaporator capacity, 3 types ○ **Cycling/Alternating/Shedding** – fans turned off/subsets of fans turned off/portion of fans shed depending on load or season ○ **Two-speed** – motors have full and half-speed settings ○ **Variable speed** – speed controlled continuously w/ VFDs
	Refrigerant transport – supply of refrigerant to evaporator coils, usually controls capacity of evaporators, 3 methods ○ **Recirculated/Overfeed** – liquid refrigerant held in low-pressure/temp receiver, pumped to coils, controlled by hand or liquid solenoid valve to provide evaporator coils with 3-4x more refrigerant than is boiled ○ **Flooded** – low-pressure/temp liquid held in adjacent "accumulator," refrigerant flows down via gravity to coil, vapor bubbles rise through coil to top of accumulator and are drawn away by compressors, pressure regulator on accumulator controls refrigerant temp/pressure ○ **Direct expansion** – high-pressure refrigerant piped to evaporator coil, thermal-expansion valve meters refrigerant flow, refrigerant flow to thermal expansion valve controlled by liquid solenoid valve
Heat exchangers ○ **Refrigerant-to-secondary fluid** – refrigerant cools a second fluid (water, glycol, brine), done with shell-and-tube, plate-and-frame, or falling-film heat exchanger ○ **Direct-contact** – refrigerant cools food product, done with shell-and-tube, plate-and-frame, etc, or scraped-surface for hardening products (ice cream, etc)	**Types of heat exchangers** ○ **Shell-and-tube** – used for cooling secondary fluids/fluid products, refrigerant passes through shell side, then tubes, uses a flooded design with a refrigerant-pressure regulator ○ **Plate-and-frame** – high heat-transfer, often have multiple heating or cooling stages ○ **Falling-film** – liquid refrigerant flows within angle/vertical plate which is cooled by secondary fluid ○ **Scraped-surface** – rotating inner drum w/ blades that scrape product from refrigerant-filled out barrel ○ **Plate freezers** – product placed on flat horizontal surface w/ refrigerant or secondary coolant on other side, slowly shifted along surface ○ **Ice scraper/maker** – flake ice made by spraying water on inner surface of vertical drum, blades scrape ice off sides – crushed/tube/cube made in specialized batch machines
Defrost systems	**Defrost controls** – 3 methods ○ **Manual** – sometimes seen in spiral freezers/freeze tunnels but becoming less common, initiated by staff ○ **Simple local controls** – controlled with dedicated local defrost controller i.e. a time clock w/ multiple set points ○ **Centralized computer-control system** – most sophisticated, unfortunately many also use time schedule and are no more efficient than local controls – more sophisticated scheduling could be based on coil load and ended based on gas temperature leaving the coil

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance.

Table 12. Compressor Technologies

COMPRESSORS – compresses refrigerant vapor by raising pressure and therefore temperature	
Reciprocating – used in low or high-temp applications, use pistons to compress refrigerant vapor in a cylinder, pistons driven by crankshaft which is driven directly by electric motor or attached to belt drive, compressed vapor exits through exhaust valve – compound compressors have multiple stages of compression in one machine have improved efficiency and extend machine's pressure range	**Capacity control** – uses a form of cylinder unloading: activated by electric solenoids managed by pressure switches, remote electro-mechanical switches or computer control (rare) – inlet valve held open by oil pressure/discharge-gas pressure, prevents cylinder from compressing, piston simply pushes suction gas back into suction line
Rotary screw – can be used in almost any refrigeration 2 types of rotary screw compressors ○ **Twin screw** – two rotors rotate and mesh together, vapor drawn into space between rotors and compressed, released to discharge port – relies on oil to seal the rotors, oil must be separated from vapor afterwards ○ **Single screw** – similar but with a single rotor and two gate rotors	**Capacity control** – 4 methods ○ **Motor speed** –, variable-speed compressors use an inverter drive to convert a fixed-frequency alternating current into one with adjustable voltage and frequency (VFD), which allows variation of motor's rotating speed; since capacity is almost directly proportional to running frequency, virtually infinite capacity steps are possible by using VFDs; two-speed motors were available in the past ○ **Variable compressor displacement (slide valve)** – virtually all compressors use – slide valves moves and point on rotors where compressions starts is changed, uncompressed gas is allowed into compressor – slide valve is usually moved by oil pressure, though new models are managed by micro-processor – can provide infinite capacity adjustment ○ **Poppet valve** –inefficient – used in booster compressors, ports along the rotor casing have valves that open to bypass compressed gas back to the suction end, thus serving as a refrigerant bypass ○ **Inlet/suction throttling** – rare, inefficient –used in booster compressors, inlet valve in the suction line closes, reducing refrigerant flow and creating vacuum between throttling valve and rotors Virtually all new screw compressors are controlled by a microprocessor panel mounted on the compressor – electro-mechanical controls can be upgraded
Rotary vane – rarely used in new facilities – used as booster compressors in low-temp applications – blades called "vanes" located in slots of the rotor are thrust outward and slide along the case as the compressor turns – can move lots of refrigerant but have limited pressure ranges, and are loud and fragile	**Capacity control** – most have none – a gas bypass feature occasionally available that recirculates high-pressure gas from the discharge line to the suction line, inefficient method Virtually all are operated manually or with simple pressure switches/computer-control system

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance and American Society for Heating Refrigeration and Air-Conditioning Engineers (ASHRAE) (2008). ASHRAE Handbook: HVAC Systems and Equipment.

Table 13. Condenser Technologies

<table>
<tr><td colspan="2">CONDENSERS – vapor enters condenser, fans blow cool air over compressor, warm refrigerant heats air and cools from vapor to liquid</td></tr>
<tr><td>Forced-draft with axial fans – fans are located on the end/side, blow air into the volume below the tube bundle – often rectangular, 1-6 with 1-4 motors per fan, 1 or 2 pumps, always belt-driven – high efficiency and simple access to fans/motors</td><td rowspan="3">Capacity control – managed by interrupting/varying water and/or air flow
○ Fan and pump cycling – pressure switches (usually spring-loaded or mercury units) cycle pumps and fans on/off – set points often staggered
○ Air flow control – many modern condensers use VFDs, speed can be varied continuously (rarely provided by condenser manufacturer, usually by electrical contractor) – 2-speed and pony motors used before VFDs
○ Water flow control – capacity mostly not controlled by water flow, can cause solids to build up on surfaces
Integral sumps hold water in a pan at the bottom of the condenser factory-installed pump simply lifts water from sump to spray nozzles, remote sump consists of large tank below condensers w/ large pumps to overcome head pressure (often installed to simplify water treatment, to provide water reservoir for defrosting/compressor cooling or in frigid climates</td></tr>
<tr><td>Induced-draft with axial fans – fans are on the top and draw air in the sides and upwards over the tube bundle – 1-4 fans, each with 1 motor, 1 or 2 pumps, driven by belts on smaller units, by shaft/gearbox on larger units – higher efficiencies, quiet</td></tr>
<tr><td>Forced-draft with centrifugal fans – fans located underneath the tub bundle and blow air into volume below bundle – 1-8 fans, each with 1-4 motors, 1 or 2 pumps, belt-driven fans – quiet, high pressure air flow</td></tr>
</table>

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance.

Table 14. Valve Technologies

<table>
<tr><td colspan="2">VALVES – perform “expansion,” liquid refrigerant passes through narrow valve, loses pressure, causing some vaporization and cooling of the liquid refrigerant</td></tr>
<tr><td>Liquid solenoids</td><td>Open/close to manage the flow of liquid refrigerant
Newly developed solenoids don’t just open/close abruptly, but modulates to meter flow – smoothes out system pressure, can also have effects on sequencing/selecting compressors</td></tr>
<tr><td>Hand expansion valves</td><td>Used to meter flow, usually w/ a liquid solenoid</td></tr>
<tr><td>Thermal expansion valves</td><td>Used on rare applications w/ direct-expansion evaporators, screw compressors, etc.
Older models use bulb-and-diaphragm design, new electronic versions have greater flexibility/control</td></tr>
<tr><td>Pressure regulators</td><td>Maintain steady pressure at inlet/outlet – common in industrial refrigeration</td></tr>
</table>

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance.

Table 15. Control Technologies

CONTROLS – evaporators controlled in response to zone temperature, compressors controlled in response to suction pressure, and condensers controlled in response to condensing pressure – additional functions: include advanced compressor sequencing, advanced condenser control algorithms, advanced demand defrost initiation and termination control, 2-speed motor and VFD control, underfloor heating system monitoring/control, trending, system alarms, and remote control	
Manual	complete management by personnel, increasingly uncommon
Electro-mechanical	Use simple pneumatic or electronic circuitry to manage equipment, still relatively common o In larger refrigeration systems, electro-mech controls can be assembled into a package o Increasingly rare in new installations, PLCs and computers replacing Contains: o **Pressure switches** – unload cylinders in reciprocating compressors and control cycling of condenser pumps/fans ▪ **Spring-loaded** – have a "cut-in" set point and a "cut-out" or "differential" set point – adjusted with a screw-driver, difficult to accurately set, susceptible to drift ▪ **Mercury** – use liquid mercury and offer cut-in/cut-out settings, easy to set and are most common on condenser controls o **Thermostat** – senses temperature change and activates a switch, most often used to control evaporator coils and associated liquid solenoids and fans
Simple programmable logic controllers (PLC)	For small systems, perform same functions as electro-mechanical controls but use solid-state hardware instead on pneumatic, thermostatic, electrical controls Common PLCS: Honeywell Universal Digital Controller, Allen-Bradley SLC 500
Computer control	2 primary varieties o **Central** – computer directly executes all control code and trending o **Distributed** – individual PLC controllers located throughout the system, central computer could be turned off and system would continue to operate Both systems use: o A system of analog and digital input/output modules to communicate with sensors and equipment, contained in panels throughout the facility ▪ Serial communications led to Modbus that uses a single communications cable rather than discrete analog and digital input/output Used to use proprietary, low-level software, now modern, open software more common Usually contains… o Evaporator liquid solenoid and pressure regulator control o Evaporator fan on/off control o Evaporator defrost control o Compressor on/off and unloading control o Condenser pump and fan on/off control

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance.

Table 16. Other Technologies

OTHER TECHNOLOGIES	
VESSELS	**Low-pressure receivers** – insulated tank that holds lo-pressure/temp liquid ammonia to be sent to evaporators
	Accumulators – also an insulated tank that holds lo-pressure/temp liquid ammonia, located above an evaporator coil/heat exchanger – most accumulators have a manual, dual-position or motorized pressure regulator between the vessel and the compressor suction line
	Intercoolers and subcoolers – o **Intercooler** – vessel that contains liquid refrigerant at an intermediate pressure in a multistage system, discharge gas from a booster compressor bubbles through refrigerant and returns to saturation temp o **Subcooler** – vessel containing liquid refrigerant in an economized subcooling system
	High-pressure receivers – uninsulated tank that holds high-pressure liquid draining from condensers – all refrigeration systems have one, can be horizontal/vertical
	Controlled-pressure receivers – a few systems use, compressor discharge gas in used to move liquid refrigerant through the coils/between vessels – pressure on the vessel is held at a constant level
UNDERFLOOR HEATING	**Glycol** – glycol runs through PVC pipes in floor beneath the freezer, pump circulates glycol though a heat exchanger in the engine room/underfloor piping – glycol usually heated w/ ammonia from compressor discharge, sometimes heating done w/ small condensing exchanger where refrigerant condenses
	Air – warm air blown through PVC piping – air sometimes ambient/engine room, some systems use refrigerant heat recovery/electric/gas heating to raise air temp
	Electric – heat tape/cable laid underneath or in the slab or concrete – usually small applications
VARIABLE FREQUENCY DRIVES (VFDs)	First used on centrifugal water chillers then screw compressors etc – only recently used in industrial refrigeration –possible to retrofit onto compressors and condensers, evaporator fans Allow energy savings from using equipment at lower speed/reduced torque
PURGERS	Used in systems operating with negative suction pressure (below atmospheric) that draw air into the system which increases condensing pressures

Source: Wilcox, M., R. Morton, D. Brown (2004). Industrial Refrigeration Best Practices Guide. Walla Walla, WA, Cascade Energy Engineering, Inc., Northwest Energy Efficiency Alliance.

Appendix B: Summary Table of Quantum Consulting's Study of Refrigerated Warehouse Facilities

In 2005, Quantum Consulting conducted a study of several agricultural food processing facilities and baking sites which participated in manual demand response reductions. Tables 17 and 18 list the results for sites with cold storage facilities.

Table 17. Agricultural Product Processing Sites Demand Response Findings

Cold Storage Sites	Site description	Strategies	Key findings
Site 2: Agricultural product processing, packing and cold storage facility (PGE, CPP)	**General Info** ▪ Fruit processing (sorting, quality control, washing, processing, packing), cold storage ▪ DR doesn't affect operations **Specific of facilities and processes** ▪ Energy costs 5%-10% facility's costs ▪ 7 buildings, 250,000 sq ft o Building 1 (Cold storage: reciprocating compressor 20hp; Office: lighting 6kW; Processing: 2 grinders 57kW, 3 packing machines 125kW, battery chargers 3kW) o Building 2 (Cold storage: 1 reciprocating compressor 75hp, 2 reciprocating compressors 60hp, condenser 10hp, evaporator fans 22 x 1hp) o Building 3 (Cold storage: reciprocating compressors 15hp) ▪ 170 staff during peak, 100 staff off-season, shifts 5-6 am till 2:30-3pm ▪ Seasonal production varies (Aug-Nov peak = 60% of production) ▪ Back-up gen. installed to reduce peak loads in summer **Main electricity end uses** ▪ 1.) Cold storage ▪ 2.) Lighting, process equipment **Participation motives** ▪ Energy bill savings and good corporate citizenship	**Planned** ▪ Planned to manually shut off 20-30% of loads via cold storage for up to 6 hrs ▪ No formal DR action plan **Implemented** Primarily cold storage reduction ▪ Cut off compressors, let temp. float, monitored products for tolerance levels ▪ Refined DR – used pre-cooling, pre-curtailment, sub-load shedding	▪ Manual cold storage curtailment were consistent and manageable reduction for longer events ▪ Processing loads significant load reducers (esp. @ peak season) but abandoned (costs, altering schedules) ▪ Manually controlling cold storage more effective than curtailing numerous process loads ▪ Back-up generator in summer diminished daily peak loads, diminishing curtailment potential
Site 4: Agricultural product processing, packing and cold storage facility (SCE, DBP)	**General Info** ▪ Fruit processing (sorting, quality control, washing, processing, packing), cold storage ▪ DR doesn't affect operations **Specifics of facilities and processes** ▪ Energy costs 10-25% of total costs ▪ 3 buildings, 174,400 sq ft (Building 1 not used) o Building 2: Cold storage, 54000 sq ft (2 ammonia chillers each 120 tons, 2 cooling tower fans each 15hp) o Building 3: Processing (air compressor 40hp, forklift charger 7.5kW, CAB grader 28kW, storage conveyor 13kW, carton former/conveyor 9kW, FMC dryer 63kW, palletizer); Washing: (4 CW pumps each 3hp, 4 water pumps 27kW); Cold storage (150 ton chiller 600 amp for 50,000 sq ft, 320 ton chiller 600 amp for 40,000 sq ft, 2 air handlers for cold storage #1, 30kW, 1 air handler for cold storage #2, 4.5 kW) **Main electricity end uses** ▪ 1.) Cold storage ▪ 2.) Process equipment **Participation motives** ▪ Energy bill savings (Indicated they would practice DR just for regular savings, even without incentives)	**Planned** ▪ Possible max. curtailment 650kW for up to 6 hrs o Expected 280kW reduction in bldg 3 o Expected 370kW reduction in bldg 2 and 3 cold storage. **Implemented** Primarily cold storage reduction ▪ Cut off compressors, let temp. float, monitored products for tolerance levels ▪ Refined DR – used pre-cooling, pre-curtailment, sub-load shedding	▪ Manual cold storage curtailment were consistent and manageable reduction for longer events ▪ Processing loads significant load reducers (esp. @ peak season) but abandoned (costs, altering schedules) ▪ Manually controlling cold storage more effective than curtailing numerous process loads ▪ Minimizing testing and service impacts allowed up to 8hr. shedding ▪ Shifting daytime loads to smaller chiller diminished curtailment potential

Source: Quantum Consulting Inc., Evaluation of 2005 Statewide Large Nonresidential Day-Ahead and Reliability Demand Response Programs: Final Report, April, 2006. Quantum Consulting Inc. Berkeley.

Table 18. Baking and Food Production Sites Demand Response Findings

Cold Storage Sites	Site description	Strategies	Key findings
Site 3: Baking and frozen storage facility (PGE, CPP)	**General site info** ▪ Baking/food production and frozen storage ▪ Food produced and immediately frozen (more in a linear process than a batch process). This method requires more time to adjust schedules **Specifics of facilities and processes** ▪ 1 large building 135,000 sq ft; Cold Storage 75,000 sq ft ▪ Production schedule fluctuates, normally 22hrs/day between 4-2am ▪ 200 staff ▪ Warehouse and freezing, mixing and baking, packaging, and office areas ▪ Equipment: (4 HVAC chillers each 60, 40, 20, 10 tons, Lighting: 3.6kW in warehouse, 8.6kW in packaging, Cold storage compressors 100 tons, Mixers 150hp, Battery chargers 10kw) **Main electricity end uses** ▪ 1.) Cold storage ▪ 2.) HVAC, lighting, process equipment **Participation motives** ▪ Avoiding blackouts and good corporate citizenship (more important than bill savings)	**Planned** ▪ Reduce cold storage and other process loads ▪ Shutting down production lines, mixers or lights ▪ Expected 200+kW curtailment **Implemented** ▪ Manual cold storage reduction with additional manual process loads (refrigeration, HVAC, lighting, processes) ▪ Overhead lighting curtailment, eventually used only daylighting ▪ Never implemented planned DR strategies	▪ Did not match load reduction of 2 and 4 ○ Moderate outdoor temps resulted in no HVAC loads to curtail
Site 12: Food production and frozen storage facility (PGE, DBP)	**General site info** ▪ Baking/food production and frozen storage ▪ Food produced and immediately frozen (more in a linear process than a batch process). This method requires more time to adjust schedules **Specifics of facilities and processes** ▪ Concerned about energy costs, 5-10% of total costs ▪ 69,500 sq ft, 95% floorspace conditioned ○ Cold Storage (Ammonia chiller 1: 450 ton, temp set point -10°F; Chiller pumps, Cooling towers: 6 glycol pumps, 7 evaporator fans, Spiral freezers) ○ Production (Ammonia chiller 2: 250 ton, temp set point 45°F; Water pump, 15 hp, Battery chargers, 10kW) ○ Warehouse (Ammonia chiller 3: 500 ton, temp set point 60°F) ○ Baking and packaging areas (Ammonia chiller 4: 250 ton, temp set point 70°F; Material transporters/conveyors, 30kW, Oven fan) ○ Small office ○ Typically 160 staff, 210 staff during summer, multiple weekday shifts, 20-22 hrs/day **Main electricity end uses** ▪ 1.) Cold storage ▪ 2.) Process equipment **Participation motives** ▪ Exploit bill savings w/out disrupting production, dissatisfied w/ projected savings	**Planned** ▪ Planned to cut off chiller compressors (raising temp 20°F (from -10° to +10°F), cold storage can maintain temps for 48 hrs if doors not opened ▪ Other possible curtailments: battery chargers, conveyors, water pumps, HVAC chillers if weather allows ○ 20% of process loads could be reduced for up to 60kW savings **Implemented** ▪ Never implemented planned DR strategies	N/A

Source: Quantum Consulting Inc., Evaluation of 2005 Statewide Large Nonresidential Day-Ahead and Reliability Demand Response Programs: Final Report, April, 2006. Quantum Consulting Inc. Berkeley.