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STATUS OF ENERGY USE AND CONSERVATION TECHNOLOGIES USED IN FRUIT AND VEGETABLE COOLING OPERATIONS IN CALIFORNIA

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Status of Energy Use and Conservation Technologies Used in Fruit and Vegetable Cooling Operations in California is the final report for the Agricultural End-use Efficiency project contract number 400-99-005, work authorization numbers #12 and #14 conducted by University of California, Davis. The information from this project contributes to PIER's Industrial/Agricultural/Water End-Use Energy Efficiency Program. For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

Interviews with produce cooling operators and refrigeration equipment installers and analysis of utility bills and production records from 14 cooling operations were used to estimate electricity use for produce cooling in California and identify conservation measures.

In 2006, cooling and short-term storage of California's 17.7 million tons fresh market fruits and vegetables consumed 977 million kWh. This represented 5.1% of the total electricity used by agriculture and 0.4% of the state's total consumption.

Large electricity savings with minimal investment can be obtained by better utilization of the refrigerated volume in existing facilities. Operators should consolidate product in the fewest number of cold rooms and shut down unneeded storage volume. Energy efficient and cost effective lighting systems are available for refrigerated environments but are rarely used in produce coolers. Operators should be made aware of the benefits of using these new lighting sources and offered incentives and to use them.

A number of other conservation options have been used successfully in commercial facilities but have varying levels of market penetration, such as: installing control software to maximize refrigerant suction pressure, adding condenser heat exchange capacity with improved refrigerant discharge pressure control, adding speed control and using software for proper screw compressor sequencing, and applying high reflectivity surface coatings. A number of other options, like installing high efficiency motors, save small amounts of electricity and are cost effective for new installations and when equipment is replaced.

Research is needed on a number of options that hold potential for economically reducing electricity use in produce coolers. Installers mentioned ideas such as determining the minimum water flow needed in hydrocoolers and optimizing airflow rate and reducing pressure drop in forced-air coolers. Possible ideas in vacuum coolers include: using a common refrigeration system for multiple vacuum tubes, minimizing the time water is sprayed in the water spray operation, using high-speed vacuum pumps, and installing direct expansion or flooded evaporators.

Keywords: electricity, refrigeration, compressor, condenser, forced-air, hydro, vacuum cooling, conservation, efficiency

Executive Summary

Cooling and short-term storage of California's 17.7 million tons annual production of fresh market fruits and vegetables consumes 1.1 million kWh. This represents 5.5% of the total electricity used by agriculture and 0.4% of the state's total consumption.

Interviews with refrigeration installers and facility managers revealed there is a wide range of steps that can be implemented to reduce electricity use, Table 1. All of the facility managers indicated they have taken some steps to reduce their electricity use. Many forced-air and hydrocooling operations have installed additional condenser capacity to reduce refrigeration system head pressures, use rapid acting exterior doors, and utilize a method of optimizing compressor sequencing. However there are no other steps that have been consistently used and there remain a number of additional conservation measures the industry can utilize.

Table 1. Electricity conservation methods for fruit and vegetable cooling facilities.

Electricity Saving Methods	Savings Potential	Market penetration
Install energy efficient lighting	8 to 16%	<5%
Minimize amount of refrigerated space and use racks or stack pallets	Up to 70%	>50% use racks or stack pallets, variable use of minimizing refrigerated space
Implement controls to maximize suction pressure	No estimate available	Low
Speed control for screw compressors	Up to 37%	Common in new vegetable coolers, 5% of fruit coolers
Optimum compressor sequencing	No estimate available	90% of new installation, <50% of existing
Add condenser capacity and improved discharge pressure control	No estimate available	>80% of new facilities, 60% of existing
Use rapid acting exterior doors	Small	Common in new facilities
Methods used for new installations and when replacing equipment: - Use high efficiency motors - Add roof or wall insulation - Increase refrigerant piping diameter - Insulate refrigerant piping	No estimate available	No estimates available, but probably common in new facilities
Use high reflectivity roofing and exterior paint	Up to 3-4%	20 to 30%
Install hydrocooler in cold room	25%	10 to 20%
Minimize hydrocooler reservoir volume	9%	No estimate available
Minimize water pump capacity	No estimate available	No estimate available
Harvest in predawn and early morning	10 to 25%	Rarely used

Installing efficient lighting, like high bay fluorescent lamps or LED fixtures when their cost drops, will produce dependable, cost-effective electricity savings and requires no management. Because it has little market penetration it should be a high priority for incentives.

Optimizing the use of refrigerated space is often requires just consolidating product in fewer rooms and turning off refrigerated space in unneeded cold rooms. Capital costs are minimal and electricity savings are great. The industry needs to:

Consolidate product and
Shutdown unneeded cold rooms.

Increasing refrigerant suction pressure can be done with computer-based control systems that are common in produce cooling facilities. The pressure can be increased when refrigeration demand drops because of reduced input of warm product or lower outside temperatures. Improved control can often be achieved by reprogramming an existing computer. No specific energy saving testing has been done for this technology.

Screw compressors are now available and older units can be retrofitted with variable speed motor control. This allows the units to operate efficiently over a wider range of refrigerant flows. Adding capacity modulation to one or at most two screw compressors will allow a well-programmed control system to efficiently operate compressors.

Applying ‘Cool Roof’ coatings and painting exterior walls with high reflectivity paint will reduce heat input from solar radiation. Electricity savings are small but this method requires no ongoing management or operating expenses.

A number of conservation methods appear to be economically feasible only when used in a new installation or when failed equipment is replaced. These include the use of high efficiency motors, adding roof or wall insulation, increasing refrigeration pipe sizing, and insulating refrigeration pipes

Refrigeration designers and installers mentioned a number of other conservation ideas that need research or field-testing. There are several approaches to reducing electricity use for fan operation in forced-air coolers. Research is needed on the cost and electricity savings for installing low airflow resistance evaporator coils, slowing evaporator fan speed when there is less refrigeration demand, proper design of airflow channels, and increasing package vent area. Storage areas may also benefit from speed control on evaporator fans or cycling single speed evaporator fans. Hydrocooler pumps appear to operate at greater water flow than is needed for rapid cooling and research is needed to determine optimum water flow rates. Potential options for reduced electricity use in vacuum coolers include using a common refrigeration system for multiple vacuum tubes,

minimizing the time water is sprayed in the water spray operation, using high-speed vacuum pumps, and installing direct expansion or flooded evaporators.

Peak period electricity demand could be reduced by partial cooling certain items during the peak period and then finishing the cooling after the peak period ends. Based on a limited test, strawberry does not appear to be suited to two-stage cooling, but a number of other produce items are likely to be good candidates for this method. More research is needed to verify the list of fruits and vegetables that can withstand two-stage cooling.

The results of this study provide public benefits to California by identifying commercially feasible methods and technologies that can be used by commercial fruit and vegetable cooling operations to reduce their electricity use.

1.0 Introduction

The California Energy Commission (CEC) previously authorized a project to determine the electricity use of refrigerated warehouses. Some fresh market fruits and vegetables are stored long term in these facilities, but most of California's 17.7 billion pounds of annual production is cooled quickly after harvest and then shipped to market with a few hours to a few days after cooling.

The last systematic study of the electricity use of this sector was in the mid 1970s. Since that time the fresh fruit and vegetable industry has continued to expand and has adopted a number of commercially available electricity conservation measures, and in some cases has switched to different initial cooling methods. A current assessment of the electricity use and types of conservation technology available to this sector will allow CEC to optimize its programs to reduce electricity consumption in this industry sector.

Cooling fresh market fruits and vegetables immediately after harvest is a critical step in maintaining quality of produce. Harvest usually begins just after daybreak and the first loads of product arrive at the cooling facility by mid morning. With many commodities, peak refrigeration loads occur in mid afternoon, during the peak rate period for electricity. For most produce items, it is not advisable to delay cooling until after the peak rate periods ends at 6PM. Delays in cooling cause loss of shelf life because of water loss, excessive respiration rates and increased decay development. Few in the perishables industry would consider delaying cooling to reduce peak period electricity use.

However, an option for reducing electricity demand without restricting the amount of product entering the cooler is to stop cooling when product reaches a temperature of 45° to 50°F. This temperature is not the final 32°-34°F temperature needed for most commodities, but is much cooler than product temperatures at harvest that range from 70° to near 100°F. At intermediate temperatures respiration rate, water loss and decay development are many times slower than at harvest temperatures. Cooling to intermediate temperatures is already commonly used in the stonefruit industry where serpentine forced-air or hydrocooling is used to partially cool fruit harvested in the late afternoon but packed in the morning of the following day. Stonefruit is not particularly perishable and lends itself to two-stage cooling. An evaluation is needed to determine the quality effects of two-stage cooling on a highly perishable commodity like strawberries.

2.0 Project Approach

The project was divided into the following four tasks.

Task 1. Determine commercially used energy conservation technologies

Interviews were conducted with refrigeration contractors who install the majority of California's forced-air, hydrocooling, vacuum, and liquid-ice cooling systems to determine the range of energy conservation methods used by their customers, the effectiveness of the measures and the market penetration of each method. A literature review was also conducted to gain additional information about conservation measures, particularly looking for commercial-scale testing.

The following refrigeration designers and installers were interviewed for the study.

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Task 2. Determine electricity use for initial cooling of fruits and vegetables

The electricity use of commercial cooling operations was determined by surveying selected produce cooling companies in California. Companies were chosen because they use one of the cooling methods included in the study and they had an electric meter

dedicated to one type of cooling method. Data for two seasons were obtained on monthly electricity use, monthly product throughput, initial and final product temperatures, installed electrical equipment, energy conservation techniques implemented, and details about how the cooling operation is managed.

Electricity use is described as kWh per ton of product cooled for the purpose of determining total electricity use in the state. However for comparing electricity use efficiency between individual operations, electricity use is described as an energy coefficient. This index accounts for the product temperature drop during the cooling operation and this varies considerably during a season and between the hot Central Valley and the cool coastal production areas.

$$EC = M \times c_p \times (T_i - T_f) / (E \times C)$$

Where:

EC = Energy coefficient

M= Mass of product (lbs)

c_p = Specific heat of product above freezing = 1 Btu/ lb-°F, actual specific heat is slightly less than this but M does not include mass of packaging material.

T_i = Initial temperature of product, °F. (This is assumed to be the daily average temperature obtained from CIMIS weather data. Harvest usually begins at day break, approximately the daily minimum temperature, and ends at mid afternoon, near the daily maximum temperature)

T_f = Final temperature of product, °F, based on data provided by facility manager.

E = Electricity purchased to cool product, kWh.

C = 3413 Btu/kWh

Heat load removed by the refrigeration equipment was calculated using standard procedures (ASHRAE, 2006) and Drown (1969) was used for ground heat transfer estimate. For product load, the thermal energy load and heat of respiration were combined. Transmission load corresponds to the heat transferred through walls and roof. The internal heat load was calculated by adding the loads coming from fans, lights, and lift trucks. To account for equipment efficiency and actual hours of operation, the following formulas were used.

a) Product load = Sensible product thermal energy load + Heat of respiration

$$\text{Thermal energy load} = M \times c_p \times (T_{ai} - T_{af})$$

where:

$(T_{ai} - T_{af})$ = Temperature change from 600 to 1600 hr = daily average air temperature

Heat of respiration was calculated by multiplying the respiration rate factor at the recommended product storage temperature (Postharvest Technology Research and Information Center, 2008) times the typical storage time for the product. Respiration rates are listed as a range. High end of the range was used for strawberries, asparagus, and lettuce that are stored for short periods. The low end of the range was used for grapes that are stored for long periods.

b) Monthly transmission load = $((U_w \times A_w) + (U_r \times A_r) + (U_g \times A_g)) \times (T_2 - T_c) \times 24\text{h/d} \times d$

where:

U_w = Wall heat transfer coefficient (Btu/ft²-h-°F)

A_w = Wall total area (ft²)

A_g = Floor area (ft²)

U_r = Roof heat transfer coefficient (Btu/ft²-h-°F)

A_r = Roof total area (ft²)

U = Ground heat transfer coefficient ((Btu/ft²-h-°F))

T_1 = Average air temperature (°F)

T_2 = Average sol-air temperature (°F)

T_c = Setpoint temperature of cooler (°F)

d = days per month

c) Internal load = Lights + Fans + Forklifts

Lighting = $N_l \times 3.41 \times W \times Ful \times Fsa \times h \times d$

where:

N_l = number of lamps

3.41 = Btu/watt-h

W = Total light wattage (W)

Ful = Lighting use factor = 1

Fsa = Allowance factor to account for ballast energy use = 1.15

h = hours per day of operation

Precooling fans = $(M_t / (M_p \times P)) \times F_h \times t$

where:

M_t = weight of product cooled per month (lb/mo)

M_p = weight of product in a pallet load (lb)

P = number of pallets in a typical cooling cycle

F_h = fan motor heat production based on nameplate power demand (Btuh)

t = typical cooling time for a pallet (h)

$$\text{Evaporator fans} = N_f \times F_h \times h \times d$$

where:

N_f = number of fans

F_h = motor heat production based on nameplate power requirement (Btuh)

$$\text{Forklifts} = N_t \times 42.5 \times C \times d \times 0.8$$

where:

N_t = number of lift trucks, assuming each use one battery charge per day

42.5 = typical battery capacity (kWh)

0.8 = battery efficiency

Total electricity consumption by lights and fans was determined by adding the total electricity required to run them and the total electricity required by the refrigeration system to remove their heat load. The electricity required by the refrigeration system to remove the heat load from lights or fans was calculated from the percentage of total heat load that corresponded to each source.

Task 3. Analysis of survey and electricity accounting data

The data collected in the previous two tasks was used to estimate total electricity use for cooling fresh market fruits and vegetables. The market penetration of commercially available and potential energy conservation technologies was also determined. These findings were used to identify areas for RD&D in the precooling industry and provide a technology road map to guide investment in future in short-term projects.

Task 4. Two-Stage Cooling Test

Field-testing of the two-stage cooling method was conducted on March 12 -13, 2008 in Camarillo, CA. Strawberries (Agoura cv) were field-packed in 1-pound clamshell containers. Each clamshell held an average of 16 berries. Eight containers were placed in each corrugated master container and master containers were stacked six per layer and 18 to 20 layers per pallet. Picking began at 8AM and four pallets were transported to the cooling facility, arriving at 10:30 AM with an average berry temperature of 55°F. Two of the pallets were cooled continuously (control treatment) to 32°F to 33°F. The other two pallets were cooled to about 40°F then held in a 36°F room for 6 hours and then returned to the forced-air cooler for final cooling to 32 to 33°F. Before cooling, 12 randomly selected clamshells (6 from each side) from each pallet were pulled out, labeled, weighed, evaluated for quality and placed back at the same places. Quality was evaluated by a single inspector grading each berry in a clamshell for the presence of

visible mold, bruising or the appearance of being over ripe. After cooling the sample clamshell containers were removed from the pallets and held for six days in cold storage (32°F) and one day at room temperature and then graded again. Clamshell weights were measured after cooling and again at the time of final grading.

3.0 Project Outcomes

Task 1: Determine commercially used energy conservation technologies

The installers identified quite a few conservation technologies and practices. They had a good understanding of which ones were well used. However, data for electricity savings for each method was often not available. When cooling operations are modified they often incorporate many conservation methods and the improved facilities may be operated differently than older facilities, so it is usually not possible to determine the specific effect of a single energy conservation method.

General Approaches to Reduce Electricity Use for Fruit and Vegetable Coolers

Energy conservation for fruit and vegetable cooling operations has several general approaches that apply to all types of coolers. Heat load added to the refrigeration system is minimized by preventing excess product warming before it arrives at the cooler, by minimizing equipment (lights, motors, vehicles) operation inside the refrigerated space, and by reducing heat entering the shell of the refrigerated space (Manaset et al., 2007). The refrigeration system is more efficient if it operates at the minimum possible difference between head pressure and suction pressure. Large heat exchanger surface area, well designed control systems, adequate refrigerant pipe sizing, and the use of evaporative condensers are some approaches to minimize the pressure difference. Each piece of the system should be operated within its range of efficient performance. For example screw type compressors are most efficient when operating near maximum capacity. Most cooling facilities have several compressors with differing maximum capacity and control systems must be set up to select the correct mix of compressors to efficiently handle the refrigeration load. Finally the control system must be designed to shut down equipment when it is not needed.

Specific Methods to Reduce Electricity Use

Product -

Minimize product heat gain between harvest and arrival at cooling facility by shading product and minimizing time between picking and delivery to cooler. This also reduces produce quality loss after harvest. Some highly perishable items like strawberries and raspberries commonly have prescribed maximum times between harvest and the start of cooling. A number of vegetable operations are tracking 'cut to cool' times and setting up procedures to manage and minimize this time.

A few vegetable crops, like melons and broccoli, have been successfully hand harvested during the coolest hours of the day, beginning several hours before dawn and finishing in the early morning. Specially designed mobile lighting

systems are used to allow harvest before sunrise. Mechanically harvested crops, like fresh-cut spinach and mixed salad greens, are also well suited to night harvest. During the hot months in the Central Valley this technique significantly reduces incoming product temperature compared to exiting harvest timing. Night picking of melons was estimated to reduce the required temperature drop by 37% (Fairbank, 1986). This would cut forced-air cooling time and therefore fan electricity use by about 20% and product heat input by 37%, reducing electricity use by an average of 19%.

Refrigeration Equipment –

1. Install variable speed drive for screw compressors. Most cooling operations use screw compressors rather than the older reciprocating units. Screw compressors have much less maintenance than reciprocating compressors but they operate with decreasing efficiency as their refrigeration capacity is reduced. The efficiency loss is particularly noticeable below 70% of maximum refrigerant flow. Large cooling operations have multiple compressors of several sizes to handle the varying refrigeration load during the day. However the load is often somewhere between the incremental maximum loads of the compressors and at least one will be operating at an inefficient capacity. Screw compressors are now available and older units can be retrofitted with variable speed motor control, usually using variable frequency drives (VFD). This allows the units to operate efficiently at lower refrigerant flows. Adding motor speed control to one or at most two compressors will allow each compressor to operate efficiently. It is common to have one compressor with speed control in new vegetable cooling operations, but less than 5% of fruit cooling operations have this capacity. PG&E has demonstrated its value in a test in vacuum cooling (PG&E 2008). One company markets screw compressors with variable compression ratio as an alternative to speed control.
2. Program the refrigeration control system to efficiently sequence the operation of screw compressors. A simple compressor control strategy is to operate the smallest unit when refrigeration demand is low and then energize the next larger compressor when demand exceeds the capacity of the first compressor. However the second, larger compressor (often twice the capacity of the first compressor) will usually be operating at partial capacity and inefficiently until load increases. One option to improve efficiency is to turn off the small compressor and more fully load the second compressor. Efficient compressor sequencing is used in about 90% of new installations but less than 50% of existing facilities have been retrofitted with efficient sequencing control. Most existing facilities have computer based control systems and could implement this control strategy. However many controllers use proprietary software and they must be programmed by the original installer, if the installer still supports the software. If software support is no longer available then a new controller must be installed and programmed, at considerable cost.

3. Increase condenser heat exchange capacity. Increased condenser surface area allows the refrigerant to be cooled to a lower temperature, resulting in a lower discharge pressure at the compressor and consequently reducing its electricity demand. For many years California utilities have provided incentives for purchasing larger evaporators and about 60% of existing facilities have been retrofitted with increased condensing capacity. More than 80% of facilities built in the last five to seven years incorporate this in their design. Most vacuum coolers are operated with portable refrigeration equipment and have some added condenser capacity. However weight and size constraints have limited the amount of capacity installed.
4. Use discharge refrigerant pressure control in combination with variable speed condenser fans. This option offers the potential of minimizing condenser fan energy use and operating the refrigeration system at optimum discharge refrigerant pressure. Reduced refrigeration demand and lower outside air temperature allows the condenser to operate at lower rate of heat rejection and lower airflow. Controllers sense outside wet bulb temperature and adjust condenser fan speed to control refrigerant leaving the condenser at 3°F to 6°F warmer than the ambient wet bulb temperature. As load or ambient temperature increase fan speed is increased to maintain the desired refrigerant temperature. Discharge pressure control is common in new installations. About 50% of vegetable cooling operations and over 80% of fruit cooling operations use this technology.
5. Reprogram the control system to use floating suction pressure. The goal of this method is to operate the refrigeration system at the highest feasible suction pressure to reduce compressor energy use. Most refrigeration systems have the pressure regulators needed to control suction pressure and this system can be implemented by software changes. However the selection of the optimum pressure has not been thoroughly evaluated. For example higher suction pressures also increase the relative humidity in the storage area and reduce produce weight loss but high pressure may require the evaporator fans to be operated at faster speeds and greater electricity demand. Floating suction pressure control is not widely used in the industry. This concept has good potential for electricity savings (USDOE 2002), but needs additional research to evaluate the competing effects of suction pressure control and other options for accomplishing optimum control. Some operators manually increase suction pressure as facilities handle less warm fruit per day and are increasingly used for storage near the end of the harvest season.
6. A competing option to suction pressure control is to intermittently operate the evaporator and keep a constant suction pressure. When air entering the evaporators (this is representative of room air temperature) reaches setpoint temperature, the evaporator fans are turned off and the refrigerant flow is stopped. One of the evaporator fans is designated as a sampling fan near the location where the thermostat senses room air temperature. This sampling fan

runs continuously or is programmed to sample the air at predetermined times. If the air temperature is above the setpoint temperature then the refrigeration in that zone will start up and cool the air to the set point and then stop. Data logs indicate a 30 to 60% reduction in fan run time and 50% reduction in defrost time with this control technique.

7. Use high efficiency motors. This is economically feasible only in new installations or when replacing failed motors.
8. Install larger refrigeration pipe size. This reduces pressure drop in refrigerant lines and allows compressors to operate at slightly reduced pressure differences. This is commonly done in new installations but usually does not save enough electricity to be a cost effective retrofit option. One disadvantage of large diameter liquid supply lines is that high outside air temperatures and solar heating can cause vapor to form in the liquid refrigerant line if the liquid flows slowly during periods of low refrigerant demand.
9. Insulate exterior liquid refrigerant lines. This reduces refrigerant heat gain and saves a small amount of electricity in the warm Central Valley. Unless the liquid refrigerant has been subcooled it typically has a temperature of 90° to 95°F and insulation will save little in the cooler coastal regions of California. Insulation is commonly installed in new installations but usually does not save enough electricity to be a cost effective retrofit option.

Electricity savings associated with improved design of refrigeration systems for produce cooling has not been well documented with commercial testing. The technical literature has some estimates of savings but the justification for the estimates is not described (Galitsky, 2005 and Masanet, 2007). It is difficult to compare the electricity use of commercial facilities from one year to the next because amount of fruit handled changes and often many conservation changes are made at one time and it is difficult to distinguish the effect of each individual change. The refrigeration designers indicated adding extra condenser surface, a well-designed control of condenser fans, proper compressor sequencing, and suction pressure control will together result in 25% to 40% electricity savings depending on the design of the unmodified system.

Forced-air coolers -

1. Use the full height of refrigerated rooms by stacking pallets or installing pallet racks, Figure 1. Product throughput effects energy efficiency, measured as kWh consumed per box, more than any other factor in an operation. (This is explained in the next task.) Increasing the use of the entire refrigerated volume is one technique for increasing product throughput. More than 50% of cooling facilities use racks to store pallets two or three pallets high. A few commodities like table grapes stack pallets directly on each other. It is common to stack pallets two high on a forced air cooler. Pallet loads made with wood end and

expanded polystyrene boxes are often stacked three pallets high in storage rooms. However the strawberry industry rarely stacks pallets or uses racks.



Figure 1. Forced-air cooler with stacked pallets.

2. Divide the cold storage into separate rooms and refrigerate each room only when needed. Another method of improving the utilization of the refrigerated space is to simply reduce the amount of space actually cooled when it is not needed. Most facilities are divided into separate rooms and each room can be cooled independently. Efficient operators concentrate product into as few rooms as possible and turn off the unused rooms. Inefficient operation of refrigerated space can increase energy use per box many fold.
3. Speed the cooling process by using airflow reversal for small diameter products. A third method of increasing throughput is to speed the cooling process. Small diameter products like berries cool in 10 or 20% less time if the airflow direction is reversed at least once during the process. At least one operation in the state is designed to do this with a system of doors in the air supply plenum and tarps that can be deployed or retracted. Several other operations use continuous flow coolers that automatically change airflow direction as the pallets pass through the cooler.
4. Reduce the fan speed near end of cooling. Many new forced air coolers have fan speed control and have the capability to slow fan speed near the end of the cooling cycle when the rate of heat loss from the product is many times lower than at the beginning of the cooling cycle. It reduces fan energy use and reduces the potential for excess moisture loss from the product if it is left on the cooler too long. About 20 to 30% of the coolers use this. However the method has not been carefully evaluated to determine when and how much to slow the

airflow. Slowing airflow too much will increase cooling time and in some coolers may reduce the amount of product that can be cooled. This increases the energy use per box of product cooled.

5. Use efficient lighting and turn off lights with motion sensors. Well over 90% of the coolers use metal halide lamps. High bay fluorescent fixtures that can operate in cold temperatures are available and use about 40% to 50% less electricity than metal halide lamps. Less than 5% of cold rooms have been retrofitted with high bay fluorescent lighting. One of the asparagus coolers in the study installed motion sensors that activate fluorescent lights when someone enters a room. Lights are turned off five minutes after there is no more motion in the room. If there is little traffic in a room motion sensors will increase savings of a new lighting system. HID lamps cannot be restarted quickly and will not work with motion sensor control.
6. Select packaging and design the cooler to minimize pressure drop across cooling fans. Fan energy use can be reduced by reducing the airflow resistance in the system.
 - Use plate fin evaporators with four fins per inch or less to minimize air pressure drop across evaporator. Spiral fin coils and coils with more fins per inch have greater pressure drop across them than the recommended coil.
 - Use adequate air supply and return channel dimensions to minimize pressure drop. Maximum air speed should be less than 1500 fpm (Thompson et al., 1998). This also produces more uniform product temperature at the end of cooling compared with excessively narrow air channels.
 - Minimize pressure drop across boxes by using packages with at least 5% side wall vent area and locate vents to allow unobstructed airflow between cross-stacked boxes on a pallet. Eliminate liner and other interior packaging if possible. Containers with every large vent areas, near 30%, can cause nonuniform cooling in facilities with narrow supply and return channels.
7. Use ‘Cool Roof’ coatings and paint exterior walls with high reflectivity paint. A PIER sponsored project (CEC 2004) estimated a 3 to 4% reduction in electricity use and a 6 to 7% reduction in demand when a stone fruit cooling and storage facility was retrofitted with a 63 to 70% reflectivity white roof covering. The facility originally had a black membrane roof (with a 6% reflectivity) and savings would have been lower if the roof were originally a typical white roof (with a reflectivity of 35 to 55%). Savings would also be less if the facility were located in coastal production areas that have more overcast conditions. About 20 to 30% of cooling facilities have installed high reflectivity roofs.

8. Reduce infiltration with rapid acting doors. Air infiltration tends to be a small part of total refrigeration load, especially with the covered docks that have become common in the industry. Many new facilities have fast acting exterior doors to minimize infiltration. Very few older facilities have been retrofitted.
9. Defrost evaporator coils by not starting refrigerant flow at the beginning of a cycle and allowing heat of the product to melt ice. This is not possible with grape coolers because evaporators must be rinsed after each cycle to remove sulfurous acid caused by the sulfur dioxide fumigation done in conjunction with initial cooling.
10. Install high levels of wall and roof insulation to reduce heat conduction from outside. This is done sometimes in conjunction with reproofing but is not likely to be cost effective in other situations.

Hydrocoolers –

1. Install the hydrocooler in a cold room, Figure 2. Heat conducted across uninsulated walls and air infiltration contributes 26% to 28% of total heat removed by a hydrocooler's refrigeration system (Thompson and Chen, 1989). Hydrocoolers are difficult to insulate because the insulation is prone to getting wet and losing its effectiveness. Also the cooler operators need easy access to the top of the cooler to clean it. The most convenient way to eliminate the exterior heat gain is to install the cooler in an insulated room. Ten to 20% of hydrocoolers are located in cold rooms. A little less than half are located outside in the direct sun and the remaining 40% are located in covered areas, protected from solar radiation.



Figure 2. Uncovered hydrocooler (left) and same hydrocooler after an insulated room was built around it (right).

2. Minimize water pump capacity. Water pumping accounts for 9% to 11% of the heat input to a hydrocooler (Thompson and Chen, 1989). There is little research

on the minimum water flow rates required to produce fast, uniform cooling. Thompson and Chen reported flow rates of 72 gallons per minute per square foot of shower pan area. Most designers interviewed indicated they specify 20 to 30 gpm per ft². Unpublished work done by the authors indicates individual cherries can be rapidly cooled with as little as 7 gpm per ft². Minimum necessary water flow is likely affected by the diameter of the product, container vent area and placement, and height of product in the cooler. More research is needed to determine optimum water flow rates.

3. Reduce water reservoir volume to speed initial cooling of water at start up and after water is changed. Older style hydrocoolers were designed with large water reservoirs. This may have been because early designs placed the refrigeration coils in this reservoir. Most coolers now place the evaporator coils on top of the cooler and there is need only for enough water to fill the pumps, piping, water distribution pan, and trash screen assembly. Thompson and Chen estimated a 9% electricity savings by reducing a large water reservoir to a minimum size. Most existing hydrocoolers have over-sized water reservoirs and reducing the volume only requires welding some metal plates in the reservoir.
4. Operate hydrocoolers at maximum capacity. Like other coolers, increasing product throughput decreases electricity use per unit cooled, primarily because the heat input through walls and infiltration is spread over more boxes of product as throughput is increased. However most operations have just one hydrocooler and the throughput rate is dependent on amount of product harvested in the field and is not under the hydrocooler manager's control.
5. Minimize water loss from cooler. Water lost in packages leaving the cooler is replaced with warm water that must be cooled. In batch-type hydrocoolers, containers should be allowed to thoroughly drain before being removed from the cooler. Continuous flow coolers are usually designed with a drain section after the product leaves the water shower area.
6. Use large diameter nozzles to distribute water over coil instead of a shower pan. This water distribution method requires less water than the typical shower pan and reduces amount of water needed to operate the cooler.
7. Use a droplet breaker if required rather than drip pan to distribute water over produce to further reduce water required to operate the hydrocooler.

Vacuum Coolers –

Vacuum coolers are batch operations with widely varying demands for refrigeration and vacuum, Figure 3. Typically a load of iceberg lettuce requires about 30 minutes to cool. After the doors of the chamber are closed the vacuum pumps are turned on and about 8 to 10 minutes are required to bring the chamber pressure to 20 to 30 mm Hg absolute pressure. At this pressure the product begins to cool as it rapidly releases water. The

water vapor released from the product is condensed on the refrigeration coils in the chamber, producing a large instantaneous refrigeration demand. It steadily tapers off for the next 20 minutes as the load finishes cooling. During the vapor release phase the vacuum pumps typically operate at about 50% demand.



Figure 3. Typical 12-pallet vacuum cooler.

1. Use variable frequency drives to modulate speed of screw compressors, condenser fans and vacuum pumps. In 2007 PG&E conducted a demonstration of variable frequency drives for a screw compressor, vacuum pump and condenser fans (PG&E 2008). They demonstrated a 29% electricity savings and a 29% reduction in demand compared with a conventional vacuum cooler. Compressor electricity use was reduced by 56% and compressors use about two-thirds of the total (Thompson and Chen, 1988). Electricity use of the condenser fan was reduced by 61% and the vacuum pump by 15%. The modified vacuum cooler would reduce electricity cost (energy and demand) by \$65,000 if operated for a 9-month season in the PG&E territory. The cost of adding the VFDs was not reported. Screw compressors with variable compression ratio can be used in place of a VFD.
2. Operate cooler at maximum product throughput capacity. Vacuum coolers lose efficiency when they are operated with less than a full load of product (Thompson et al., 1987). Operators should combine lots to fill a chamber when they have this option. But usually they must cool product as it arrives, rather than hold back some warm product until they can assemble a full load. Product quality is more important to them than energy cost.

Except for the two studies mentioned above, there has been relatively little energy efficiency research conducted on vacuum coolers. The installers interviewed suggested a number of concepts that could be evaluated to reduce electricity consumption, but they need to be tested before being recommended.

1. Use a common refrigeration system with compressor sequencing control for multiple vacuum tubes. This allows screw compressors to operate in their efficient range more hours of the day.
2. Minimize the time water is sprayed in Hydrovac operation. This would reduce electricity use of the water pump and reduce the time water is gaining heat from contact with the shell of the cooler.
3. Use high-speed vacuum pumps to reduce connected horsepower and to improve vacuum pressure load matching. Performance specifications for high speed vacuum pumps indicate they are more efficient than the conventional pumps used by the industry.
4. Install direct expansion or flooded evaporators to eliminate ammonia pumps.

Ice Manufacturing Plants.

1. Reduce amount of ice added to each carton to 50% of normal. This will still allow for good product cooling and some humidification of air around the product while allowing a significant reduction in energy used for manufacturing ice. The challenge in this option is to get a uniform ice fill in each box on a pallet load.
2. Evaluate other initial cooling methods to replace ice cooling, Figure 4. Ice cooling is the least energy efficient method because large amounts of ice are added to the box solely for the purpose of preventing product moisture loss.



Figure 4. Liquid ice injection machine.

Task 2. Determine electricity use and conservation measures installed for fruit and vegetable cooling facilities

Electricity use

Data were collected from the 14 operations described in Table 2. Data were also collected from a third asparagus operation, but the utility meter was not read on a regular schedule and the billed electricity use during the harvest season did not appear to match monthly asparagus packout. Data from this operation was not included in the report. No data is included for package ice coolers because the refrigeration for this method is usually connected to several other cooler types and it was not possible to find a facility where electricity use could be directly associated with liquid ice cooling. This method is limited primarily to cooling a single commodity, broccoli.

Table 2. General description of cooling facilities included in the electricity use survey

Facility code	Commodity cooled	Location	Seasonal capacity (million lbs)	Refrigerated area (ft ²)
Forced-air coolers, all with refrigerated storage				
G-1	Table grapes	Delano	19-25	55,000
G-2	Table grapes	Delano	50-80	132,000
S-1	Strawberries, misc. berries	Watsonville	30	35,000
S-2	Strawberries, misc. berries	Santa Maria	38	35,000
S-3	Strawberries, misc. berries	Watsonville	97-116	63,776
S-4	Strawberries, misc. berries	Oxnard	62	20,000
S-5	Strawberries, misc. berries	Oxnard	63	45,000
Vacuum coolers, none include refrigerated storage				
L-1	Lettuce, misc. vegetables	Salinas	62-114	
L-2	Lettuce, misc. vegetables	Salinas	46	
L-3	Lettuce, misc. vegetables	San Luis Obispo	53	
L-4	Lettuce, misc. vegetables	Oxnard	113	
L-5	Lettuce, misc. vegetables	Oxnard	32	
Hydrocooler, all with refrigerated storage				
A-1	Asparagus	Lodi	1.2-2.9	5,900
A-2	Asparagus	Lodi	1.4-4.9	11,076

Forced-Air Cooling

This method had an average electricity use of 54 kWh/ton. Forced-air coolers have a great deal of heat input from sources other than the product being cooled, Figure 5. Product heat load accounts for half of the total heat input to the refrigeration system.

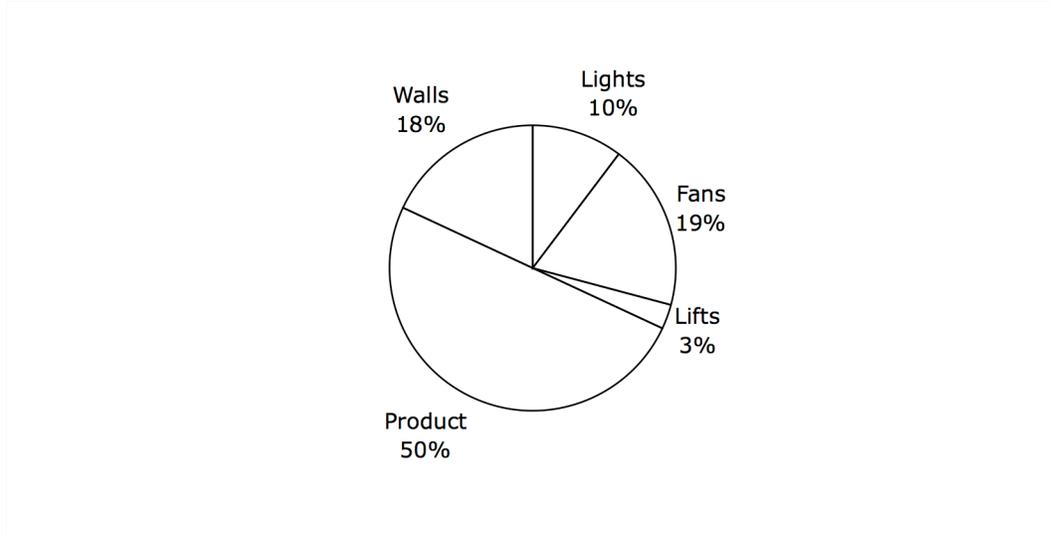


Figure 5. Average heat input to a forced-air produce cooler

Some of these heat sources also consume electricity. When the direct electricity use is added to the refrigeration electricity used to remove the heat from each source, fan operation and lighting combine to represent 46% of the electricity use in an average cooler, Figure 6. Product cooling is only 36% of the total electricity use.

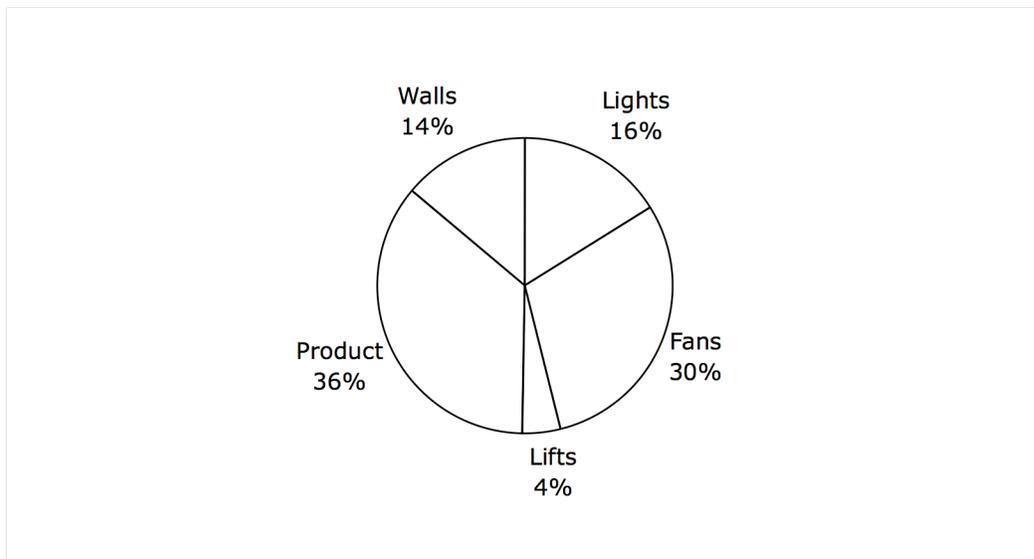


Figure 6. Combined direct electricity use and refrigeration electricity use to cool the major heat sources in forced-air coolers.

Operating fans and removing the heat they produce contributes is nearly as much electricity use as product cooling. Fan energy use is controlled by the amount of air that must be moved to cool the product, the pressure drop the fans must operate against and total cooling time. Increasing the amount of box venting reduces pressure drop and can speed cooling. It is the most economically feasible way to reduce fan electricity use. Vent area should be greater than 3% of sidewall area to minimize total costs (Baird, et al. 1988). Although not mentioned in their study, other packaging materials, like consumer bags and box liners, can also restrict airflow and increase fan energy use. The installer survey described above lists additional methods of reducing fan energy use.

All but one of the operations in the survey used standard 400W HID lamps. This type of light source cannot be restarted quickly and all fixtures need to be operated continuously as long as there is activity in the facility, often for 12 to 16 hours per day. The total heat from a lamp and its ballast equals about 460 W, eight of these lamps require about one ton of refrigeration to remove their heat production. Manufacturers claim new T5 or T8 high bay fluorescent fixtures designed for cold environments produce equivalent amount light for about 40% to 50% less electricity consumption compared with HID lamps. Fluorescent lamps can be restarted, allowing them to be turned off when not needed. Asparagus cooler A-2 recently installed high bay fluorescent lamps controlled with a motion sensor. All of the lamps in the cold room are turned off after five minutes with no activity in the room. Installing energy efficient lighting systems is clearly a promising method for reducing electricity consumption and demand.

Economics of a Lighting Retrofit

Before the start of the 2008 harvest season, a grape cooling and cold storage company in the San Joaquin Valley retrofitted their 400 W HID fixtures with high bay fluorescent fixtures. The new fixtures were a sealed stainless steel design with six-T8 fluorescent tubes and an electronic ballast. The old units were replaced one of one with the new, so there was minimal rewiring. The 89 fixtures were replaced at a cost of \$36,900 and the local electric utility provided a \$100 per fixture rebate. Fifty-five of them were in refrigerated areas and 24 of these were located in storage areas with little traffic and were controlled by motion sensors with a 20 minute delay. The sensors cost \$80 each.

Electricity savings for the fixtures in ambient temperature locations was the difference between the rated wattage of the fixtures: $460\text{W} - 221\text{W} = 239\text{W}$. In the refrigerated areas there is additional saving because less heat must be removed by the refrigeration system. Based on data from forced-air cooling facilities, each watt of reduced lighting will reduce refrigeration electricity use by 0.8 watts. Table 3 summarizes the simple payback times for the new fixtures. Grape cooling and storage facilities typically operate for 150 days per year. The high bay fluorescent fixture installation with motion sensors has a simple payback in 210 days, during the second month of the second season of operation. The new fixtures without motion sensors have a payback in 250 days. These fixtures are located in areas with high traffic levels and adding motion sensors would improve the payback period only if their daily use period were reduced below about 12

hours per day. The retrofitted lights in the outside area pay back in nine years. The extended pay back is caused by their need to operate only six hours per day, between sunset and midnight, and because they have no savings associated with reduced refrigeration demand.

Table 3. Cost, electricity savings and payback for installing high bay fluorescent lights in a grape cooling and storage facility.

Fixture location	Installed cost per fixture ¹ (\$)	Operation period per day ² (hr)	Electricity savings @ \$0.15/kWh (\$/day)	Simple payback period (days)
Outside in unrefrigerated area	293	6	0.22	1360
Refrigerated area	293	16	1.03	280
Refrigerated area with motion sensor	373	8	1.51	250
Refrigerated area with motion sensor	373	4	1.75	210

¹ Capital and installation cost minus rebate

² Facility operates from 8AM to midnight, motion sensor is assumed to reduce hours of lighting by 50% or 75%

Individual cooling operations had very different energy use efficiencies as measured by EC, Table 4. On an individual season basis some facilities have a six-fold higher EC, meaning they use six times more electricity to do the same amount of cooling work. Even on a facility average basis there is a 4.4 fold difference between the least and most efficient. The majority of the difference between efficiencies is explained by differences in product throughput, Figure 7. Facility S-4 has a product throughput that can exceed 1400 lb/ft²-mo on the busiest month and has an EC exceeding 1.2. Early in the season when daily strawberry harvest volumes are low because of cool or rainy weather, product throughput is less than 400 lb/ft²-mo and EC is below about 0.4. The other two facilities never exceed 400 lb/ft²-mo during their busiest months and their EC is similar to facility S-4 in its low volume months.

Facility S-4 achieves high throughput by reversing airflow through the pallets during the last third of the cycle to reduce cooling time. A brief series of tests, not reported here, indicated this reduces cooling time to about 70 min. compared with 90 min. for conventional cooling. But more importantly the cooler operators hire a person whose sole responsibility is to check berry temperature and remove product from the cooler as soon as it has reached desired temperature. During their busiest month in April 2007, each forced-air cooling tunnel in S-4 averaged 7.9 batches (8-pallets per batch) of strawberries per day. However each cooling tunnel in facility S-2 averaged only 2.3 batches per day during the same busy month.

Table 4. Seasonal average energy coefficient for forced air coolers.

Facility	Season	Average Energy Coefficient	Average Electricity Use (kWh/ton)
S-4	2006	0.71	20
	2007	0.69	19
G-2	2005	0.58	40
	2006	0.46	70
G-1	2005	0.50	48
	2006	0.40	55
S-5	2006	0.52	36
	2007	0.34	43
S-3	2004	0.32	53
	2005	0.36	48
	2006	0.32	53
S-1	2006	0.28	58
	2007	0.27	57
S-2	2006	0.12	147
	2007	0.20	63

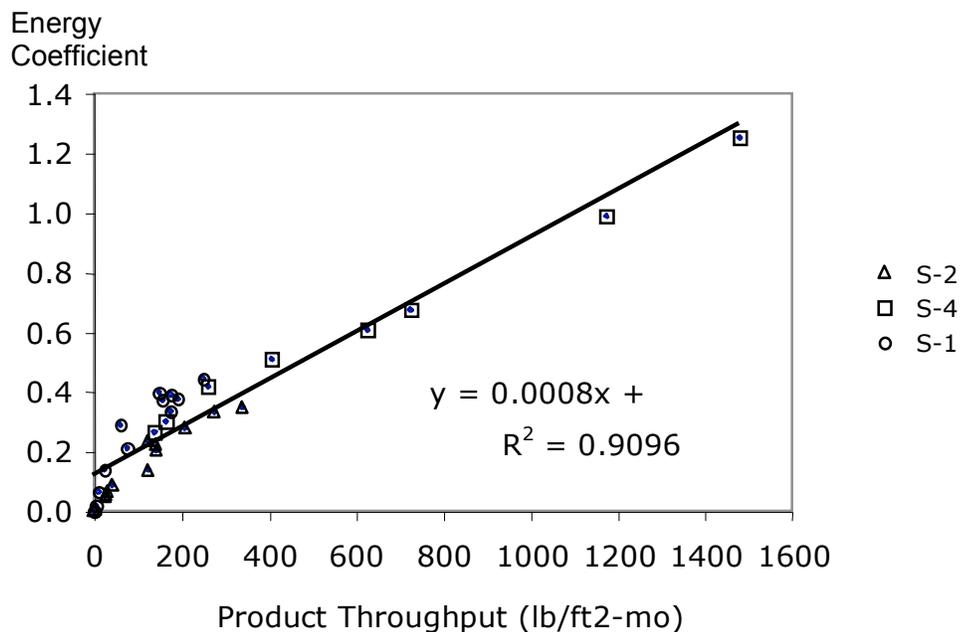


Figure 7. Effect of monthly product throughput on energy coefficient for three strawberry forced-air cooling facilities

High product throughput increases electricity use efficiency because it decreases the relative proportion of heat not associated with product cooling. For example in facility S-1, on a maximum throughput month the product heat load is 54% of the total and lighting and transmission equal 33%. In the high throughput facility S-4, in a maximum capacity month, 72% of the refrigeration load is from product cooling and only 5% is from lighting and transmission.

Table grape cooling facilities G-1 and G-2 show a similar effect of product throughput on EC, but have higher ECs at lower throughputs, Figure 8. As with strawberries, months with little fruit grape throughput have ECs below 0.20 and maximum throughput months are several times higher.

One possible reason for table grapes achieving a higher EC at lower throughputs than strawberries is grapes are grown in a much warmer environment. Temperature drop during grape cooling ranges from 30° to 50°F, while it is about half as much in strawberries, ranging from 20° to 33°F. This means that over twice as much cooling work is accomplished for each pallet of table grapes compared with a pallet of strawberries.

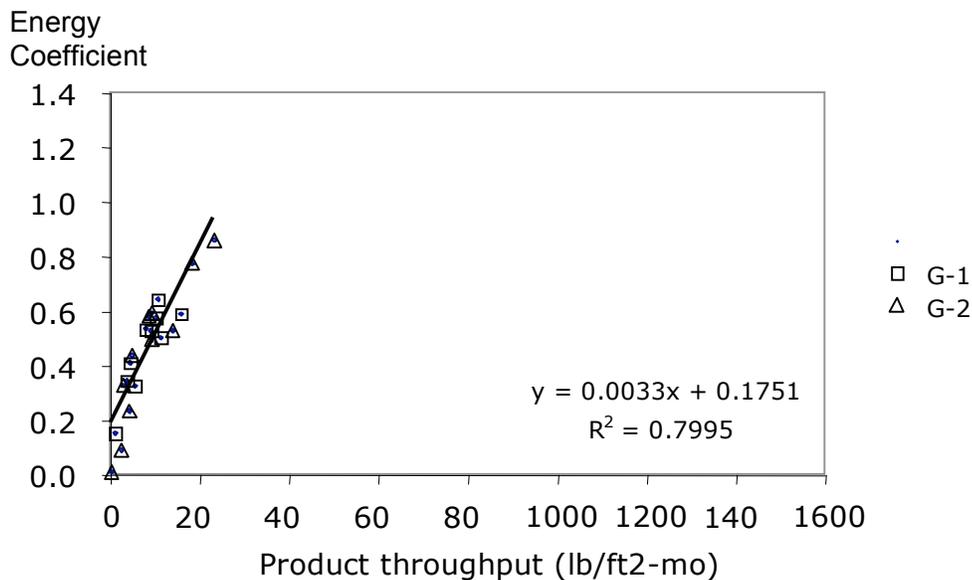


Figure 8. Effect of monthly product throughput on energy coefficient for two table grape forced-air cooling facilities

The strawberry and grape data both support the importance of maximizing the use of a refrigerated facility. Some operations use pallet racks or stack pallets to double or triple the amount product in a refrigerated area, although this is rare in strawberry cooling facilities, Figure 9. The amount of product varies greatly during the season and facilities should be partitioned to allow sections to be closed off and the refrigeration shut down in

unnecessary areas. Good management of refrigerated volume holds great potential for reducing electricity use in forced-air cooling.



Figure 9. Strawberry cold storage room with unused space.

Hydrocooling

Hydrocooling has a lower heat input and electricity use for the pumps moving the cooling medium compared with the fans used in forced-air cooling, Figures 10 and 11. Water is a more efficient heat transfer medium than air and less total mass of cooling medium is required to cool with water compared with air. Lighting heat input and electricity use is also lower in hydrocooling than forced air. This is probably due to the particular hydrocooling operations included in the survey. Operations A-1 installed high bay fluorescent fixtures with motion sensors before the 2007 season. Facility A-2 had conventional HID fixtures but an installed capacity of only 0.54 W/ft². This is near the minimum of the 1.2 to 0.49 W/ft² range for forced air coolers.

Electricity use and energy coefficient numbers are within the same range as forced-air cooling, Table 5. But the data for individual years are often in the upper portion of the range. The average electricity for hydrocooling is 107 kWh/ton compared with 54 kWh/ton for forced-air cooling.

Hydrocoolers like forced-air coolers, are more efficient as their capacity increases, Figure 12. At maximum throughput of about 1400 lb/ft²-mo their energy coefficient is near 0.5. Typical production is often less than 400 lb/ft²-mo and energy coefficients are usually less than 0.2.

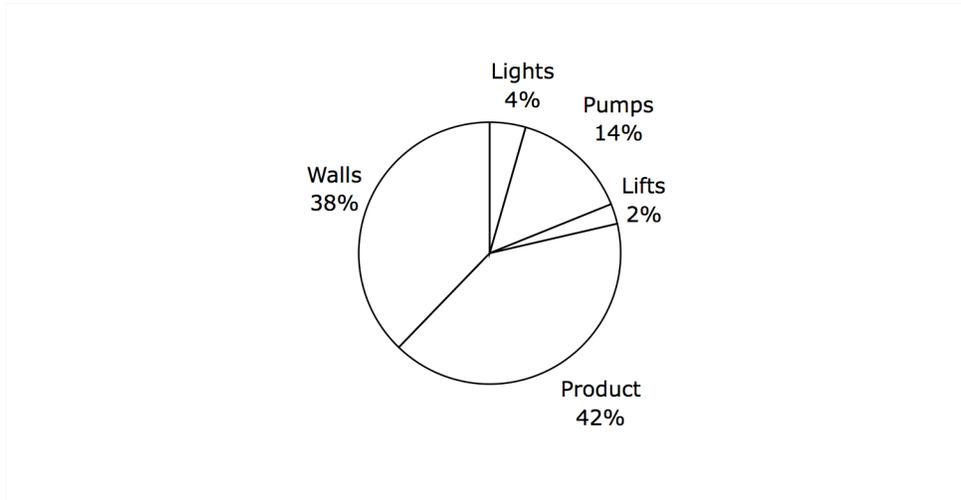


Figure 10. Average heat input to a hydrocooler

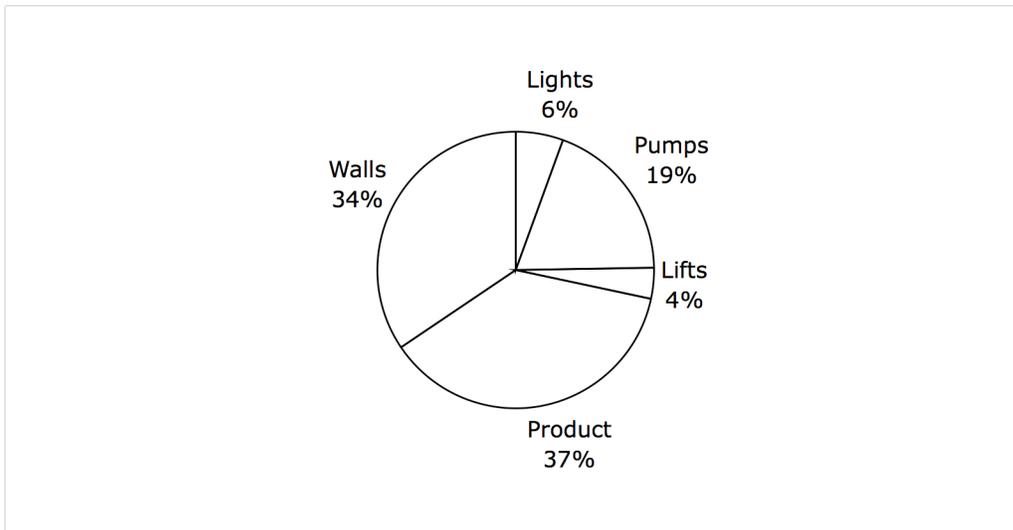


Figure 11. Combined direct electricity use and refrigeration electricity use to cool the major heat sources in hydrocoolers.

Table 5. Seasonal average energy coefficient for hydrocoolers

Facility	Season	Average Energy Coefficient	Average Electricity Use (kWh/ton)
A - 2	2006	0.13	136
	2007	0.50	42
A - 1	2006	0.10	159
	2007	0.18	94

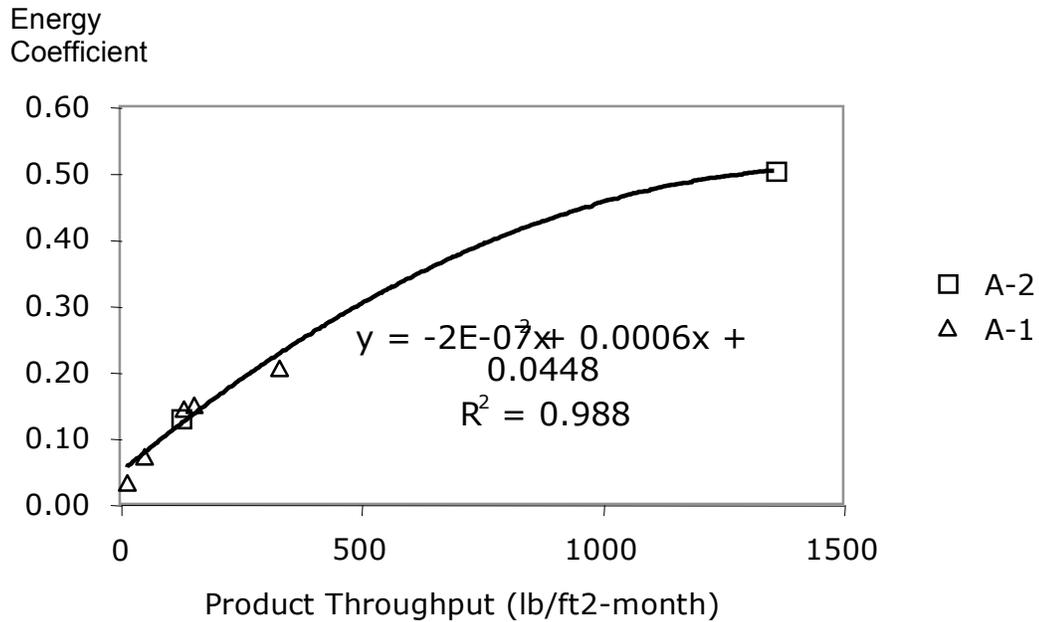


Figure 12. Effect of rate of product throughput on energy coefficient for hydrocoolers.

Vacuum Cooling

Usually vacuum cooling has no heat loads other than the product being cooled and has high energy coefficient numbers, Table 6. An exception is when water is sprayed on the product during the cooling cycle. The additional heat load is associated with cooling the water and some of the spray may run along the interior of the vacuum tube and gain heat from the ambient temperature metal. The facilities data includes loads cooled with a water spray but the amount of product cooled in this fashion was not identified.

The electricity use is very low for vacuum cooling, Table 6. This is partly because there are few or no heat loads other than the product. But the main reason is there is no product storage capacity included in the electricity use data. Most coolers are portable and are operated as a separate entity from the short-term storage. A great deal of the electricity use data reported is from the 1984 -1985 harvest season because it was difficult to find companies willing to share recent information. However there appears to be little difference between the older and the recent data. The basic vacuum cooling concept is quite simple and little has been done to reduce electricity use over the years, especially considering it is quite energy efficient. The PE&E study referenced above describes the most comprehensive experiment with reducing electricity use.

Table 6. Seasonal average energy coefficient for vacuum coolers

Facility	Season	Average Energy Coefficient	Average Electricity Use (kWh/ton)
L - 3	1984-85	1.1	12
L - 2	1984-85	1.0	14
L - 5	1984-85	1.0	12
L - 4	1984-85	0.99	13
L - 1	2005	0.94	17
	2007	0.74	19

Like the other forms of cooling, vacuum cooling shows greater efficiency with greater product throughput, Figure 13. Although the difference in energy coefficient between a maximum and a minimum product throughput month is not large compared with the differences seen in forced-air and hydrocooling. The lower efficiency is probably due to a greater frequency of partial loads being cooled when harvest rates are low. For the sake of keeping good product quality the operators do not want to leave a partial load of lettuce uncooled, waiting for additional product to arrive from the field.

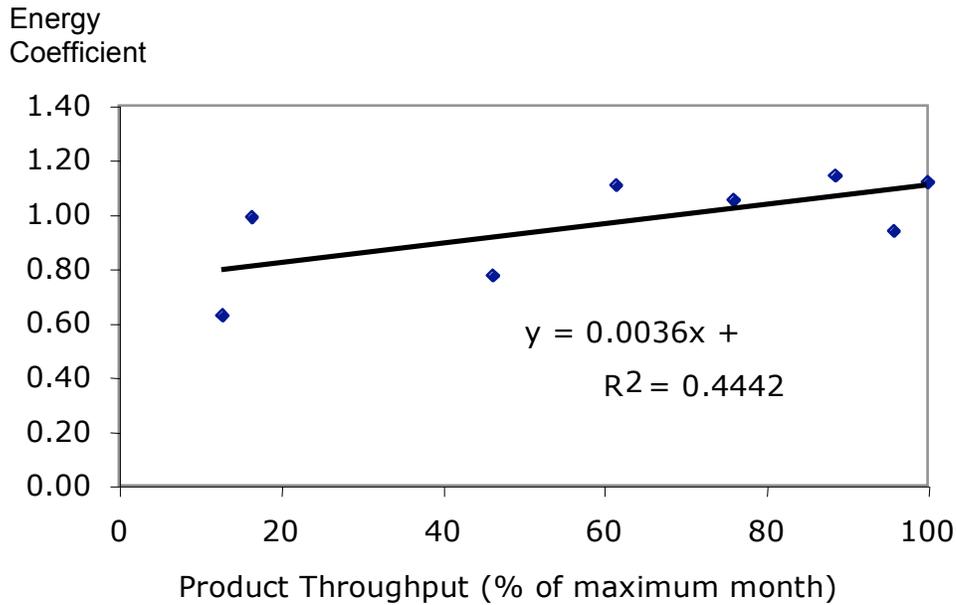


Figure 13. Effect of product throughput on energy coefficient for facility L-5.

Energy Conservation Methods Survey

Interviews with facility managers revealed that all of them have taken some steps to reduce electricity use, Table 7. The most common method was to add extra condenser capacity to reduce head pressure in their refrigeration system. Most indicated the larger condenser was fitted with variable speed fans. Even those who did not mention this probably have this capability as it is needed to get the extra condensing capacity to function well with the refrigeration system. It is possible to drop the head pressure too low if fan speed control is not included in the design of an oversized condenser.

Other conservation measures were less frequently mentioned. Only one facility installed energy efficient fluorescent lighting, all of the others use 400 W HID lamps. Another facility manages their refrigerated space carefully, closing off rooms and shutting down refrigeration when it is not needed. This facility also had the highest product throughput of any forced-air cooling facility, indicating they manage their facility quite intensively. This a key method for reducing electricity use.

Table 7. Electricity conservation measures used in cooling facilities.

Facility code	Energy conservation measures installed based on interview with facility manager
Forced-air coolers including refrigerated storage	
G-1	Added condenser capacity, 2-speed evaporator fans in coolers and VFD on evaporators in storage rooms
G-2	Added condenser capacity, VFD on condenser fans, optimum compressor sequencing, maintain high suction pressure, VFD on evaporator fans
S-1	Turn off fans & lights when not needed, replace failed motors with high efficiency motors
S-2	Close off rooms & turn off refrigeration if room not needed
S-3	Added condenser capacity
S-4	Added condenser capacity
S-5	(no interview conducted)
Vacuum coolers, no refrigerated storage included	
L-1	(no interview conducted)
L-2	(no interview conducted)
L-3	(no interview conducted)
L-4	(no interview conducted)
L-5	(no interview conducted)
Hydrocooler including refrigerated storage	
A-1	VFD on condenser fans
A-2	Added condenser capacity, VFD on condenser fans, Installed T8 fluorescent lamps with motion sensor, added roof insulation

Task 3. Analysis of survey and electricity accounting data

In 2006 California produced 17.7 million tons of fresh market fruits and vegetables. Based on the estimates of electricity use for each cooling method, 997 million kWh were used in 2006 for initial cooling and short-term storage. This represents 5.1% of the total electricity used by agriculture and 0.4% of the state's total consumption (CEC 2005). Electricity use by commodity is listed in Tables 8 and 9.

Table 8. Annual Electricity use for cooling California vegetable crops

Commodity	Annual Production (1000 tons)	Primary Cooling Method	Final Temperature (°F)	Electricity Use (kWh/ton)	Adjusted Electricity Use* (kWh/ton)	Electricity Use (kWh/yr)
Artichokes	37.6	Hydro	32	108	108	4,055,400
Asparagus	30.0	Hydro	36	108	96	2,880,000
Beans, snap	30.0	Hydro	45	108	77	2,304,000
Broccoli	920.8	Liquid ice	32	108	108	99,441,000
Cabbage	303.6	Vacuum	32	39	39	11,840,400
Carrots	1,052.3	Hydro	32	108	108	113,648,400
Cauliflower	322.2	Forced-air	32	54	54	17,396,100
Celery	850.5	Hydro	32	108	108	91,854,000
Corn, sweet	228.7	Hydro	32	108	108	24,694,200
Cucumbers	58.7	Room	54	54	32	1,876,800
Garlic	215.0	Room	32	54	54	11,610,000
Lettuce, head	2,125.0	Vacuum	32	39	39	82,875,000
leaf	740.3	Vacuum	32	39	39	28,869,750
romaine	672.0	Vacuum	32	39	39	26,208,000
Melons, cantaloupe	551.3	Hydro	41	108	84	46,466,341
honeydew	175.3	Forced-air	50	54	35	6,058,368
watermelon	320.4	Forced-air	59	54	29	9,382,454
Mushrooms	57.1	Forced-air	32	54	54	3,080,700
Onions, spring	164.0	Room	32	54	54	8,853,300
Onions, summer (non-storage)	263.2	Room	32	54	54	14,212,800
Onions, summer (storage)	675.8	Room	32	54	54	36,490,500
Peppers, bell	462.5	Room	50	54	35	15,984,000
Peppers, chili	82.5	Room	50	54	35	2,851,200
Pumpkins	57.5	Room	59	54	29	1,684,068
Spinach	231.0	Vacuum	32	39	39	9,009,000
Spinach, processed	50.0	Vacuum	32	39	39	1,948,050
Squash	82.6	Room	50	54	35	2,854,656
Tomatoes	574.0	Room	55	54	31	18,034,036
Total	11,333					696,462,524

* Electricity use is based on cooling the product from 64°F to 32°F. If a commodity is not cooled to 32°F the electricity use factor has been reduced proportionately.

Table 9. Annual electricity use for cooling California fruit crops

Commodity	Annual Production (1000 tons)	Primary Cooling Method	Final Temperature (°F)	Electricity Use (kWh/ton)	Adjusted Electricity Use* (kWh/ton)	Electricity Use (kWh/yr)
Apples	77.5	Forced-air	32	54	54	4,185,000
Apricots	9.0	Forced-air	32	54	54	486,000
Avocados	135.0	Forced-air	45	54	38	5,184,000
Blueberries	5.0	Forced-air	32	54	54	270,000
Boysenberries	1.8	Forced-air	32	54	54	98,010
Sweet cherries	32.4	Hydro	32	108	108	3,499,200
Dates	19.6	Room	32	54	54	1,058,400
Figs, fresh	7.6	Forced-air	32	54	54	410,400
Grapefruit, all	201.0	Room	59	54	29	5,886,915
Grapes, table	614.0	Forced-air	32	54	54	33,156,000
Kiwifruit	23.4	Forced-air	32	54	54	1,263,600
Lemons	798.0	Room	55	54	31	25,071,709
Nectarines	218.0	Forced-air	32	54	54	11,772,000
Olives, fresh	23.0	Forced-air	50	54	35	794,880
Oranges, Navel & misc.	1,762.5	Room	48	54	36	63,450,000
Oranges, Valencia	506.3	Room	48	54	36	18,225,000
Peaches, processed	359.0	Forced-air	32	54	54	19,386,000
Peaches, fresh	242.0	Forced-air	32	54	54	13,068,000
Pears	229.0	Forced-air	32	54	54	12,366,000
Plums	158.0	Forced-air	32	54	54	8,532,000
Raspberries	58.1	Forced-air	32	54	54	3,134,700
Strawberries	827.1	Forced-air	32	54	54	44,663,400
Tangerines, etc	135.0	Room	45	54	38	5,184,000
Total	6,442.2					281,145,214
Total fruits & vegetables	17,776					977,607,738

* Electricity use is based on cooling the product from 64°F to 32°F. If a commodity is not cooled to 32°F the electricity use factor has been reduced proportionately.

Electricity use factors for the cooling methods are calculated based on arithmetic averages of the use for the organizations that provided data, Table 10. The refrigeration systems for the forced-air and hydrocooling operations also included cold storage for holding the product after cooling. For many commodities the storage is used to hold product for a few hours to several days prior to their shipment to market. A portion of the table grape production is stored up to three months before shipment. However it was not possible to separate electricity use for grape storage from the total so the electricity consumption factors include the electricity use for this longer-term storage. Grape cooling and storage operations typically stack pallets as much as three pallets high and efficiently use the entire refrigerated volume. Their efficient use of refrigerated volume probably explains why the electricity consumption factor for table grapes is close to that of the strawberry forced-air coolers.

Table 10. Electricity consumption for five methods for initial cooling and short-term storage of fresh market fruits and vegetables

Cooling Method	Survey-based Electricity Consumption (kWh/ton)	Electricity Use Factor, including cooling and storage (kWh/ton)
Vacuum	13	39
Hydro	86	108
Forced-air	54	54
Room	NA	54
Liquid ice	NA	108

The hydrocooler electricity use was based on data for two seasons from two asparagus facilities. The electricity use data ranged widely, from 42 to 159 kWh/ton, Table 5. The 2006 season was cold and had a great deal of rain, reducing product throughput by 60 to 70% for the two facilities. Because electricity use efficiency is so closely related to product throughput, the electricity use factor was based just on the 2007 season data, where near normal harvest levels were encountered. The average energy coefficient for the 2007 season was 0.34. This is quite low compared with the earlier published data of 1.4 (Thompson and Chen, 1988). The earlier data did not include short-term storage electricity use. Electricity use for product cooling is slightly more than 50% of the total for cooling and storage, so the energy coefficient might be about double, 0.68 without the short-term storage. This is still low compared with the published data and may indicate that asparagus facilities are not used near their maximum capacity. However, having no other electricity use data, the factor in Table 10 is based on the 2007 season asparagus data.

Asparagus is cooled to 36°F although many crops are hydrocooled to 32°F. The average air temperature during asparagus harvest is about 52°F, so the typical temperature reduction for asparagus is 16°F. Crops cooled to 32°F would experience a temperature drop of 20°F and to account for this the electricity use factor was increased by 25%, from 86 kWh/ton to 108 kWh/ton.

The vacuum cooling data collected did not include refrigeration electricity use for short-term storage although the leafy green vegetables cooled by this method are always held in cold conditions after initial cooling. The electricity use for short-term storage in vacuum cooling operations was estimated based on the data for forced-air operations. In forced-air cooling, the floor area dedicated solely to cooling is less than half the total and it is used for cooling for less than half the day. Therefore electricity use for product cooling was assumed to be the refrigeration effect needed to remove product heat and half the fan horsepower. Electricity use for cooling the product equaled 36% of the total, Figure 6, and assuming half of the fan electricity use is used for initial cooling, then cooling equals 51% of the 54 kWh per ton electricity use. Electricity use for short-term storage is then

49% of the total and equals 26 kWh/ton. Electricity use for vacuum cooling averages 13kWh/ton so the total for vacuum cooling and storage is estimated to equal 39 kWh/ton.

The average energy coefficient for all the vacuum coolers equaled 0.99. This is much lower than the 1.8 documented in Thompson and Chen (1988) and lower than listed in the PG&E study. However the data in Table 6 are based on actual facility records and are quite consistent. There was no convincing reason to modify the data based on the earlier research. Energy coefficient data can be quite high for individual cooling runs, as Thompson and Chen reported, compared with monthly average data that may include partial load cooling and extended equipment idling between batches.

No data were collected for room cooling but it is very similar to forced air cooling except the cooling process lasts about 24 hours instead of about 1.5 hours for strawberries and about 8 hours for table grapes. The longer cooling times increase the amount of heat input to the system from infiltration and conduction, but the fan energy is lower. Assuming these factors are offsetting, room cooling would have the same electricity consumption factor as forced-air cooling.

No data were collected for package icing because it is limited mostly to cooling broccoli. One reference for this method (Thompson et al. in Kader, 2002) indicates package icing has an energy coefficient range from equal to forced-air cooling to several times greater than forced-air cooling. However the referenced energy coefficient data does not include electricity use for short-term storage. Adding in the electricity use for storage would significantly increase the electricity use for package-icing. The electricity consumption factor for package icing was assumed to equal that of hydrocooling.

Task 4. Two-Stage Cooling Test

The two-stage cooling method was not statistically significant different from the standard cooling method in total time in the cooler, weight loss, or amount of fruit with defects, Tables 11, 12, 13. However there was considerable difference in the amount of fruit with defects between the two cooling methods. A test with more replication and especially a test where the fruit were harvested at higher ambient temperatures may likely show significant differences in both these factors. The strawberry industry places high value on fruit quality and it is unlikely they would want to pursue this concept based on the berry quality data in Table 13.

Table 11. 4/5ths cooling time for strawberries forced-air cooled continuously or with the two-stage cooling method

Sample	Standard cooling		Two stage cooling	
	Pallet 1	Pallet 2	Pallet 1	Pallet 2
1	42.64	61.14	49.70	43.86
2	48.10	81.00	42.00	*
3	61.44	48.60	61.13	37.93
4	56.25	*	48.50	42.93
Pallet Mean	52.11	63.58	50.33	41.57
Treatment Mean		57.84		45.95

* temperature sensor fell out of fruit.

Table 12. Strawberry weight loss for strawberries forced-air cooled continuously or with the two-stage cooling method

	Precool wt	Postcool wt	Day 7 wt
Two Stage Cooling	19.81	19.54	19.07
Weight loss (%)	-	1.37	3.72
Standard Cooling	19.13	19.03	18.49
Weight loss (%)	-	0.53	3.36

Table 13. Strawberries with defects (bruise or decay) for continuously forced-air cooling or with the two-stage cooling method

Treatment	Day 0 Defective Berries (%)	Day 7 Defective Berries (%)	Increase in Defective Berries (%)
Two Stage Cooling	5.51	58.66	53.15
Standard Cooling	4.21	48.78	44.57

Strawberries and raspberries are some of the very most perishable fruits and many other items are suited to two-stage cooling. For example it is standard practice for stone fruit (peaches, plums and nectarines) to be partially cooled to about 45° to 50°F the day of harvest and then held over night at that temperature. The following day the fruit is packed and cooling is finished after the fruit is packed. Based on this common practice a wide range of commodities should be adapted to two-stage cooling. Thompson et al. (2001) listed a number of fruits and vegetables that could withstand cooling delays similar to peaches and nectarines and it is reasonable to expect they would also be suited to two-stage cooling, Table 14.

Table 14. Allowable maximum cooling delay between harvest and the start of cooling for fresh market fruits and vegetables. The delay times are estimates, actual field temperatures and product quality at harvest may modify the actual acceptable delay period. Adapted from Thompson et al. 2001.

Acceptable delay time between picking and the start of cooling (hours)				
2 hr	4hr	8 hr	16 hr	24 hr
Vegetables				
	Asparagus	Artichoke	Dry garlic	
	Broccoli	Cauliflower	Dry onion	
	Mushroom	Carrot	Potato	
	Spinach	Cucumber	Sweetpotato	
	Sweet corn	Green beans	Tomato	
	Leafy Greens	Green Onion		
		Summer squash		
Fruits and melons				
Strawberry	Apricot	Avocado	Honeydew melon	Apple
Raspberry	Grape	Cantaloupe	Pear	Grapefruit
Loganberry	Kiwifruit	Mandarin	Persimmon	Lemon
	Sweet cherry	Peach	Plum	
		Nectarine	Pomegranate	
		Watermelon		

4.0 Conclusions and Recommendations

Cooling and short-term storage of California's 17.7 million tons of fresh market fruits and vegetables consumes 1.1 million kWh. This represents 5.5% of the total electricity used by agriculture and 0.4% of the state's total consumption.

Energy Efficiency Best Practice Opportunities:

All of the interviewed facility managers indicated they have taken some steps to reduce their electricity consumption. Most forced-air and hydrocooling operations have installed additional condenser capacity to reduce refrigeration system head pressures, use rapid acting exterior doors, and utilize a method of optimizing compressor sequencing. However there are no other steps that have been consistently used and there remain a number of additional conservation measures the industry can utilize.

Improved management of refrigerated space is the most effective energy conservation method and requires little and in some cases no capital investment. Electricity use per ton of product is highly dependent on the amount of product a facility handles. Intensively managed facilities can handle three times more product per square foot than less efficiently managed facilities. On the basis of seasonal average electricity use, intensively managed facilities can use two thirds less electricity per box of produce than inefficiently managed coolers. Techniques for efficient management include: removing product from a cooler as soon as it is finished, stacking pallets or using pallet racks, and sectioning the facility to allow refrigerated areas to be shut down when not needed.

Installing energy efficient lighting is a straight-forward method to reduce electricity consumption. Operating lights and removing the heat they produce equals 16% of the electricity use in forced-air cooling operations. It represented only 6% of electricity use in hydrocoolers but the facilities in the study either used low lighting levels or had installed efficient lighting. Because of this the forced-air cooling data probably best represents the produce cooling industry. A number of companies market fixtures for T8 or T5 fluorescent lamps that are designed for cold environments. These can be restarted easily and are suited to control with a motion sensor, either turning the lights completely off or switching them to a low light level when there is no activity in a room. The fixtures must be specifically selected to operate in relative humidity levels of 80 to 90%. Grape cold storages have the additional constraint of using weekly sulfur dioxide fumigations. Electronics must be protected from this highly corrosive gas.

No detailed testing has been done with motion controlled fluorescent fixtures, but depending on the operational characteristics of a particular facility lighting electricity use should be reduced by 50% and perhaps much more. Based on average electricity use this corresponds to more than 8% reduction in total electricity use. The cost of retrofitting HID fixtures with fluorescent ones can be paid back in just over one season of use. Very few cooling and cold storage operations have changed to energy efficient lighting.

Increasing refrigerant suction pressure to maximum levels decreases refrigeration electricity use. This can be done with computer-based control systems that are common in produce cooling facilities. The pressure can be increased when refrigeration demand decreases because of reduced input of warm product or lower ambient temperatures. The controller evaluates refrigeration demand in all areas of the facility and increases suction pressure to the highest level that will allow each evaporator to provide adequate refrigeration capacity. In some cases the improved control can be achieved by reprogramming an existing computer. But many control systems use proprietary software and may require the original programmer to make the changes, if the programmer still supports the software. No specific energy saving testing has been done for this technology.

Electricity use for screw compressor can be reduced by using efficient capacity modulation and by programming the compressors to be efficiently sequenced as refrigeration load varies. Unlike older reciprocating compressors screw compressor do not operate efficiently at reduced capacity, especially below 70% of maximum. Large cooling operations have multiple compressors of several sizes to handle the varying refrigeration load during the day. However the load is often somewhere between the incremental maximum loads of the compressors and at least one will be operating at inefficient capacity. Screw compressors are now available and older units can be retrofitted with variable speed motor control. One company accomplishes much the same thing with a variable compression ratio system. This allows the units to operate efficiently over a wider range of refrigerant flows. Adding efficient capacity modulation to one or at most two compressors will allow each compressor to operate efficiently. The recent PG&E study on speed control for vacuum cooler motors estimated a 56% screw compressor electricity saving and compressors consume about two-thirds of the total electricity use. Vacuum coolers vary from no refrigeration load to hundreds of tons about two times per hour and often have a single 500 horsepower compressor. Other produce cooling operations have much less variation in refrigerant demand, multiple compressors and should expect much lower electricity savings.

A number of conservation methods appear to be economically feasible only when used in a new installation or when failed equipment is replaced. These include the use of high efficiency motors, adding roof or wall insulation, increasing refrigeration pipe sizing, insulating refrigeration pipes.

Heat input from solar radiation can be minimized by applying 'Cool Roof' coatings and painting exterior walls with high reflectivity paint. A PIER sponsored project (CEC 2004) estimated a 3 to 4% reduction in electricity use and a 6 to 7% reduction in demand when a stone fruit cooling and storage facility was retrofitted with a 63 to 70% reflectivity white roof covering. The facility originally had a black membrane roof (with a 6% reflectivity) and savings would have been lower if the roof were originally a typical white roof with a reflectivity of 35 to 55%. Savings would also be less if the facility were located near coastal production areas that have more overcast conditions.

Installing hydrocoolers in an insulated cold room reduces heat input to the coolers by 26% to 28%. Less than one fifth of the coolers in the state are located in cold rooms.

Electricity demand for produce cooling could be reduced by partial cooling certain items during the peak rate period and then finishing the cooling after the peak. Strawberry does not appear to be suited to two-stage cooling, but a number of other produce items are likely to be good candidates for this method. More research is needed to verify the list of fruits and vegetables that can withstand two-stage cooling.

Research and Development Opportunities:

Refrigeration designers and installers mentioned a number of other conservation ideas that need research or field-testing. There are several approaches to reducing electricity use for fan operation in forced-air coolers. Research is needed on the cost and electricity savings for installing low airflow resistance evaporator coils, slowing evaporator fan speed when there is less refrigeration demand, proper design of airflow channels, and increasing package vent area. Storage areas may also benefit from speed control on evaporator fans or cycling single speed evaporator fans. Hydrocooler pumps may operate at greater water flow than is needed for rapid cooling and research is needed on determining optimum water flow rates. Potential options for reduced electricity use in vacuum coolers include using a common refrigeration system for multiple vacuum tubes, minimizing the time water is sprayed in the water spray operation, using high-speed vacuum pumps, and installing direct expansion or flooded evaporators.

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