ENERGY USE OF COMMERCIAL FORCED-AIR COOLERS FOR FRUIT

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ABSTRACT. *Analysis of utility bills, facility equipment and operation, and production records from seven forced-air cooling operations were used to document the range of electricity use for commercial forced-air cooling facilities, to evaluate the electricity use and conservation options for the major system components, and to estimate annual electricity use for forced-air cooled produce in California.*

Electricity use was greatest for fruit cooling, with nearly as much for direct operation of fans plus removing the heat they produce. Electricity for operating and cooling lights, removing heat gain through walls and operating and cooling lift trucks comprised the next largest energy uses in decreasing order of use. Options for reducing electricity use of each system are discussed.

Efficiency of electricity use was measured by an energy coefficient (EC), an index calculated as the amount of cooling work accomplished divided by the amount of electricity purchased by the cooling facility. Monthly average EC varied widely at individual facilities and between facilities. Much of the variability was correlated with differences in product throughput. High throughput rates resulted in high energy efficiencies.

Based on California's fresh market fruit and vegetable production in 2006, and the electricity use data from the commercial operations, the state's produce industry consumed 186 million kWh of electricity for forced-air cooling and short-term storage during 2006.

Keywords. *Electricity, Energy, Efficiency, Refrigeration, Conservation, Forced-air cooling, Fruit.*

California is the leading producer of fresh market fruits and vegetables in the United States. The key postharvest technology allowing the state to market perishable produce over long distances is the ability to cool produce quickly after harvest. Forced-air cooling of fruits and vegetables is a common method for initial cooling and is the primary method of cooling for 20 types of fresh market fruits and vegetables grown in the state (Kader, 2002). Packaged produce is placed next to an air plenum that forces refrigerated air to flow through the packages and past the individual pieces of produce. This reduces cooling time in comparison with simply placing uncooled, packaged produce in a refrigerated room.

Virtually all forced air coolers are operated using electricity for the refrigeration equipment, lights, fans, lift truck battery charging, and other miscellaneous uses, like office equipment, pumps for storm water, etc. The authors are aware of no published information on the electricity use of forced-air cooling. However electricity use efficiency for commercial cooling operations has been described using an energy coefficient (EC), an index calculated as the amount of cooling work accomplished divided by the amount of electricity purchased by the cooling facility (Thompson and Chen, 1988). They reported an EC = 0.4 for forced-air cooling, lower than the other commonly used cooling methods: vacuum, hydro, and water-spray vacuum cooling.

The authors are aware of no literature describing the energy saving options specifically for forced-air cooling. However the system is similar to many other types of food refrigeration operations such as cold storage and freezing. Masanet et al. (2007) summarized a range of conservation methods for refrigerated fruit and vegetable processing facilities. Heat load can be reduced by reducing fan and lighting use in the refrigerated volume, minimizing air infiltration, and insulating refrigerant piping. The heat load from produce can be reduced for a few vegetable crops by harvesting them during the coolest hours of the day, beginning several hours before dawn and finishing in the early morning compared with the standard practice of starting harvest at dawn and finishing at mid-day. For fresh market melons, this was estimated to reduce the temperature drop during cooling by 37% (Fairbank, 1986). High reflectivity roof coatings reduced electricity use in a fruit cooling operation by an estimated 3% to 4% (CEC, 2004). Masanet et al. (2007) also described refrigeration equipment modifications such as adding improved equipment controls to increase suction pressure, decreasing condenser pressure, optimizing the speed of screw compressors, minimizing evaporator fan operating time and air volume, and using improved lubricant cooling methods.

The lack of current electricity use information and the lack of published information on conservation methods or forced-air cooling operations was the motivation for this

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work. The specific objectives were to collect information on electricity use of commercial forced-air cooling facilities and to describe conservation options related to reducing heat input and improving facility management.

Materials and Methods

The electricity use of commercial forced-air cooling operations was determined by surveying seven strawberry/ bushberry and table grape cooling companies in California (table 1). Many other commodities utilize forced-air cooling but the large farming companies, typical of the state, often raise many produce items and employ several methods of initial cooling on the same electric meter and it is not possible to separate out the electricity use of the individual cooling methods. However, strawberry and table grape facilities use only forced-air cooling and rarely handle other types of produce and were well-suited for the survey method used in this study. Strawberries and table grapes are the two largest crops that use forced-air cooling in California. The surveyed facilities handled about 18% of the strawberry/bushberry production and 7% of the table grape production of California.

All facilities had a cold storage area integrated into their operation. Cold storage is used for temporary storage ranging from a few hours to a few days for the strawberry/bushberry operations. The table grape operations ship some fruit immediately after initial cooling and store some grapes for up to three months to allow shipment after the end of the harvest season. Large portions of the refrigerated volume of grape facilities is devoted to storage in comparison to the volume devoted to forced-air cooling.

For most facilities, two seasons of data were obtained on monthly electricity use, monthly fruit throughput, and initial and final fruit temperatures. Facilities S-3 and S-5 provided information only on season total electricity use and product throughput. A valuable approach to understanding electricity conservation options is to estimate the major heat loads of the system. Facility managers also provided information on the number, nameplate electricity demand, and hours of use of fans and lights installed in refrigerated spaces; building dimensions; insulation type and thickness in walls and the ceiling (these facilities do not have floor insulation); exterior surface finish and color; the number of lift trucks in use, their battery capacity and hours of use in the refrigerated spaces; and size and design of exterior opening doors. Facility S-5 did not provide information on facility design or operation.

Table 1. Description of forced-air cooling facilities included in the electricity use survey.

Facility Code	Commodity Cooled	Location	Seasonal Capacity (1000 MT)	Refrigerated Area[a] (m^2)
G-1	Table grapes	Delano	9-11	5,100
G-2	Table grapes	Delano	23-36	12,300
S-1	Strawberries, bushberries	Watsonville	14	3,300
S-2	Strawberries, bushberries	Santa Maria	17	3,300
S-3	Strawberries, bushberries	Watsonville	44-53	5,900
S-4	Strawberries, bushberries	Oxnard	28	1,900
S-5	Strawberries, bushberries	Oxnard	29	4,200

[a] All facilities were single story with a wall height of approximately 7 to 8 m.

Electricity use was described as kWh per metric ton (MT) of fruit cooled to estimate industry-wide energy use. However for determining electricity use efficiency an energy coefficient (EC) was calculated for each month of operation. It is similar in concept to a coefficient of performance of a refrigeration system except the system boundary is drawn around the entire refrigerated facility. This index accounts for the temperature drop during cooling in addition to the weight of produce cooled. Temperature drop varies considerably during a season between the hot Central Valley region of California where table grapes are grown and the cool coastal production regions where berries are grown.

$$EC = M\,c_p\,(T_i - T_f)/\,(E\,c) \qquad (1)$$

where

EC = energy coefficient (kJ heat energy removed/kJ of electricity consumed)

M = mass of product cooled per month (kg/mo)

c_p = specific heat of product above freezing = 4.19 kJ/ kg-°C, actual specific heat is slightly less than this but M does not include mass of packaging material.

T_i = initial temperature of product (°C). (This is assumed to be the daily average temperature obtained from CIMIS weather data (CDWR, 2008). Harvest usually begins at dawn, approximately the daily minimum temperature, and ends at mid afternoon, near the daily maximum temperature).

T_f = final temperature of product (°C) based on data provided by facility manager.

E = electricity consumed per month to operate cooling facility (kWh/mo)

c = 3600 kJ/kWh

The electricity consumed by the cooling facility includes electricity to operate refrigeration equipment, lights, fans, and battery chargers for lift trucks.

The electricity used by the refrigeration equipment is dependent on the heat it must remove and the relative amounts of the major heat loads in a facility provide clues to potential efficiency improvements. Heat loads were calculated using standard procedures (ASHRAE, 2006). The facilities are quite large and initial estimates of air infiltration showed it was a small portion of the total and was ignored in the calculations. For product load, the thermal energy load and respiration heat of the fruits were combined. Transmission load corresponds to the heat transferred through walls, roof, and floor, the latter calculated with a method reported by Drown (1969). The internal equipment heat load was calculated by adding the loads coming from fans, lights, and lift trucks. The following formulas were used to calculate refrigeration heat loads.

$$PL = M\,c_p\,(T_i - T_f) + M\,R\,e\,t_s \qquad (2)$$

where

PL= monthly product heat load (kJ/mo)

R = respiration rate (mL CO_2/kg-h)

e = 0.510 = conversion for respiration rate (mL CO_2/ kg-h) to heat production per day (kJ/kg-d)
t_s = time in storage (days)

Heat of respiration was calculated by using tabulated respiration rates at the recommended product storage temperatures (Postharvest Technology Research and Information Center, 2008). Respiration rates are listed as a range. High end of the respiration rate range was used for strawberries that are stored for short periods immediately after cooling. The low end of the range was used for grapes that are stored for long periods.

$$TL = (((U_w A_w) + (U_r A_r)) (T_2 - T_c) + (U_g A_g) \times (T_1 - T_c)) \, 24 \, d \quad (3)$$

where
TL = monthly building transmission heat load (kJ/mo)
U_w = wall heat transfer coefficient (kJ/m^2-h-°C)
A_w = wall total area (m^2)
U_r = roof heat transfer coefficient (kJ/m^2-h-°C)
A_r = roof total area (m^2)
U_g = ground heat transfer coefficient (kJ/m^2-h-°C)
A_g = floor area (m^2)
T_1 = average ambient air temperature (°C)
T_2 = average sol-air temperature (°C), (ASHRAE, 2005)
T_c = setpoint temperature of cooler (°C)
d = days per month
24 = h/day

$$LL = N_l \, W \, f \, F_{ul} \, F_{sa} \, h_l \, d \quad (4)$$

where
LL = monthly lighting heat load (kJ/mo)
N_l = number of lamps
f = 3.6 kJ/W-h
W = lamp electrical demand (W)
F_{ul} = lighting use factor = 1
F_{sa} = factor to account for ballast energy use = 1.15
h_l = hours per day of operation

FL = precooling fans + evaporator fans in storage areas (5)

$$\text{Precooling fans} = (M_t / (M_p P)) \, F_h \, t \, c$$

where
FL = monthly fan heat load (kJ/month)
M_t = weight of product cooled per month (kg/month)
M_p = weight of product in a pallet load (kg)
P = number of pallets in a typical cooling cycle
F_h = fan motor heat production based on nameplate power demand (kW)
t = typical cooling time for a cooling cycle (h)

$$\text{Evaporator fans} = N_f \, F_h \, h_f \, d \, c$$

where
N_f = number of fans
F_h = motor heat production based on nameplate power requirement (kW)
h_f = hours per day of operation (h)

$$FLL = N_t \, 42.5 \, c \, d \, i \quad (6)$$

where
FLL = monthly forklift heat load (kJ/month)
N_t = number of lift trucks, assuming each use one battery charge per day based on the facility survey information
42.5 = typical battery capacity (kWh)
i = battery efficiency, assumed = 0.8

Electricity use associated with the five major heat sources was calculated based on the electricity required to remove the heat load of each, plus the direct electricity use in the case of the lighting, fans, and lift trucks.

$$LE = LL/c + (E - (LL + FL + FLL)/c) \, (LL/(PL + TL + LL + FL + FLL)) \quad (7)$$

where
LE = monthly lighting electricity use (kWh/mo)

$$FE = FL/c + (E - (LL + FL + FLL)/c) \, (FL/(PL + TL + LL + FL + FLL)) \quad (8)$$

where
FE = monthly fan electricity use (kWh/mo)

$$FLE = FL/(c \, i) + (E - (LL + FL + FLL)/c) \, (FLL/(PL + TL + LL + FL + FLL)) \quad (9)$$

where
FLE = monthly forklift electricity use (kWh/mo)

$$PE = (E - (LL + FL + FLL)/c) \, (PL/(PL + TL + LL + FL + FLL)) \quad (10)$$

where
PE = monthly product cooling electricity use (kWh/mo)

$$TE = (E - (LL + FL + FLL)/c) \, (TL/(PL + TL + LL + FL + FLL)) \quad (11)$$

where
TE = monthly building transmission heat cooling electricity use (kWh/mo)

Refrigeration equipment design and control are important factors affecting electricity use. Large industrial

Table 2. Average heat input to forced-air fruit coolers.

Facility	Year	Seasonal Average Heat Input (million kJ)				
		Fruit	Building	Fans	Lights	Lifts
S-1	2006	1063	425	208	367	43
	2007	532	237	109	213	22
S-2	2006	695	479	145	181	55
	2007	1066	342	258	157	63
S-3	2004	3219	928	751	911	423
	2005	3806	951	891	927	512
	2006	3327	914	779	907	436
S-4	2006	1787	177	416	88	67
	2007	1855	153	411	88	66
G-1	2005	1290	535	57	181	18
	2006	966	544	43	178	14
G-2	2005	3983	1230	1101	352	33
	2006	2552	1199	693	423	21
Average		2011	624	451	383	136
Percent of total		56	17	13	11	4

refrigeration facilities like these are custom designed and there are many options for equipment design and control that will reduce electricity use. It was not possible for a survey method like we used to evaluate the electricity use of the wide range of equipment and control systems.

Results and Discussion

Forced-air coolers have a great deal of heat input from sources other than the fruit being cooled (table 2). Fruit heat load accounts for slightly more than half of the total heat input to the refrigeration system.

Fans, lights, and lift trucks directly consume electricity in addition to being a refrigeration heat load. When their direct electricity use is added to the refrigeration electricity used to remove the heat they produce, fan operation and lighting combine to represent 45% of the electricity use in an average cooler (table 3). Fruit cooling was only 36% of the total electricity use.

The electricity used to operate fans and remove the heat they produce is nearly equal to that used for fruit cooling and represent significant opportunities for conservation. These facilities have one set of fans for forcing air past the fruit and evaporator coils in the forced-air cooling operation. Another set of fans is built into the ceiling-mounted evaporators that are used to maintain temperature in the storage areas.

Electricity use for the forced-air cooling fans is controlled by the amount of air that must be moved to cool the fruit, the pressure drop the fans must operate against, and product cooling time. Increasing the vent area in boxes reduces pressure drop and usually speeds 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, but vent areas greater than 5% are rarely used in corrugated fiberboard boxes because of excessive reduction in box strength (Baird et al., 1988). Vigneault and Goyette (2002) recommended the vent area should be 25% of the container walls for efficient cooling, but this level of venting is feasible only for plastic boxes. Although not mentioned in either study, other packaging materials, like consumer bags and box liners, also restrict airflow through a box and their use should be minimized.

Table 3. Combined direct electricity use and refrigeration electricity use to cool the major heat sources in forced-air coolers.

		Seasonal Average Electricity Use (1000 kWh)				
Facility	Year	Fruit	Building	Fans	Lights	Lifts
S-1	2006	335	157	131	247	27
	2007	174	72	70	125	14
S-2	2006	482	381	358	200	37
	2007	444	174	318	126	46
S-3	2004	929	285	722	547	254
	2005	1022	272	783	537	297
	2006	989	290	749	554	266
S-4	2006	295	38	247	45	32
	2007	279	36	240	48	30
G-1	2005	181	77	298	80	8
	2006	120	70	276	75	6
G-2	2005	666	270	528	188	16
	2006	630	431	406	351	12
Average		504	196	394	240	80
Percent of total		36	14	28	17	6

In the strawberry coolers, evaporator fans used for cooling the storage areas contributed 25% to 60% of the total fan heat input. It was well over 90% of the fan heat load in the table grape facilities, where a significant amount of fruit is long-term stored. Evaporator fan airflow rate is designed to accommodate the design maximum refrigeration load but most of the time, evaporators operate in conditions requiring much less than maximum refrigeration capacity and peak airflow rates are not needed for heat exchange. Either fan cycling, operating the fans at maximum capacity for a fraction of the time, or slowing fan motor speed are used to reduce airflow when evaporators operate at less than maximum refrigeration capacity. Evaporator airflow is also used to distribute cold air in the refrigerated space and the fan modulation system must also guarantee all parts of the space are adequately supplied with refrigerated air. Most of the surveyed operations used fan speed control to minimize electricity use. The surveyed facilities were not evaluated to determine if they effectively used fan modulation, but the operators usually survey fruit temperature and set fan speed high enough to eliminate warm areas in storage rooms.

All of the operations in the study used standard 400-W high intensity discharge (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. Manufacturers claim new T5 or T8 high bay fluorescent fixtures designed for cold environments produce an equivalent amount of light for about 40% to 50% less electricity consumption compared with HID lamps.

Another option for reducing electricity for lighting is to simply use less lighting. Installed lighting power in the surveyed facilities varied from a maximum of 12.9 W/m^2 to less than half this amount and there was no indication from the facility managers that the lower lighting levels were inadequate. Proper design of a lighting system entails much more than prescribing lighting power per square meter and is beyond the scope of this study. Fluorescent lamps can be restarted, allowing them to be turned off with motion sensors when an area has no human occupancy. Lighting can be reduced even more by using a task lighting approach, where light is used only where it is needed. Most worker activity in these rooms is associated with lift truck operation and it may be possible to install a majority of the lighting on the lift trucks and light only the area viewed by the driver.

The average EC for all facilities was 0.4, the same as reported 20 years earlier by Thompson and Chen (1988). However individual cooling operations had very different electricity use efficiencies (table 4). On an individual season basis, the most efficient facilities have a six-fold higher EC than the least efficient facilities, meaning they use one-sixth the electricity to do the same amount of cooling work. Even on a facility average basis, there is a 4.4 fold difference between the most and least efficient. The majority of the difference between efficiencies is strongly correlated with differences in product throughput (fig. 1). All of the facilities were single story designs with wall heights of 7 to 8 m, so they would show a very similar correlation to product throughput per refrigerated volume. On the busiest month, facility S-4

Table 4. Seasonal average energy coefficient and electricity use for forced air coolers.

Facility	Season	Season Average Energy Coefficient	Season Average Electricity Use (kWh/MT)
S-4	2006	0.71	22
	2007	0.69	21
G-2	2005	0.58	44
	2006	0.46	77
G-1	2005	0.50	53
	2006	0.40	60
S-5	2006	0.52	40
	2007	0.34	48
S-3	2004	0.32	59
	2005	0.36	53
	2006	0.32	59
S-1	2006	0.28	64
	2007	0.27	62
S-2	2006	0.12	162
	2007	0.20	69
Average		0.40	59
Standard deviation		0.17	32

had a product throughput that exceeded 60 kg/m^2-month with 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 about 7 kg/m^2-month and EC is less than 0.3. The other two facilities never exceed 15 kg/m^2-month during their busiest months and their EC is similar to facility S-4 in its low volume months. While there is no standard method for determining the maximum throughput capacity of individual facilities, the data clearly show managers should operate their facilities to maximize the fruit throughput per unit of refrigerated area.

Facility S-4 achieves high product 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 practice reduces cooling time to about 70 min compared with 90 min for conventional cooling. But more importantly, the cooler manager designates 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, facility S-4 had an EC of 1.25 and each forced-air cooling tunnel averaged 7.9 batches (assuming 8-pallets per batch) of strawberries per day. However facility S-2 had an EC of 0.35 and each cooling tunnel averaged only 2.3 batches per day during the same busy month.

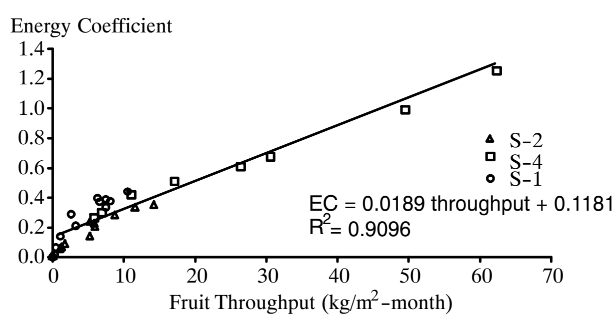

Figure 1. Effect of monthly fruit throughput on energy coefficient for three strawberry forced-air cooling facilities.

High fruit throughput increases electricity use efficiency because it decreases the proportion of heat load not associated with product cooling. For example, the maximum throughput of facility S-1 is 11 kg/m^2-month and during that month the fruit heat load is 54% of the total and lighting and transmission loads equal 33% of the total. The maximum throughput of facility S-4 is 60 kg/m^2-month and during that month, 72% of the total load is from fruit cooling and only 5% of the load is from lighting and transmission.

Table grape cooling facilities G-1 and G-2 show a similar effect of fruit throughput on EC (fig. 2). Months with maximum fruit throughput have ECs exceeding 0.80 and during months with minimum throughput ECs rarely exceed 0.20.

Grape cooling facilities have higher ECs at lower product throughput rates compared with strawberry facilities. Part of the reason for this is grapes are grown in a much warmer environment. Temperature drop during grape cooling ranges from 17°C to 28°C compared with 11°C to 18°C for strawberries. Based on median temperature drop during cooling, the grape facilities do 60% more cooling work (see eq. 1) for each unit mass of table grape throughput compared with strawberries. In addition, the grape facilities reach maximum cooling capacity at lower throughput rates per unit of total refrigerated area because they devote only about 10% of their refrigerated area to forced-air cooling. While strawberry facilities typically have 30% to 50% of their refrigerated area devoted to forced-air cooling.

The strawberry and grape data both support the importance of maximizing the product throughput of a refrigerated facility. Pallets are stacked two or three high in grape forced-air coolers, while pallet stacking is not done in strawberry coolers. Table grape facilities also stack pallets three high in storage areas to minimize the refrigerated storage volume needed in relation to the volume needed for forced-air cooling. Strawberry facilities never stack pallets but a few use pallet racks in storage areas, although this is rare (fig. 3). The monthly product throughput varies greatly during the season and facilities should be partitioned to allow sections to be closed off and the refrigeration shut down in unused areas.

The annual electricity use for forced-air cooling produce in California was estimated based on the average electricity use of 59 kWh/MT (table 4). Some commodities are not cooled to 0°C and their electricity use factor was decreased in proportion to their reduced temperature drop during cooling. In 2006 California produced 3.5 million MT of fresh

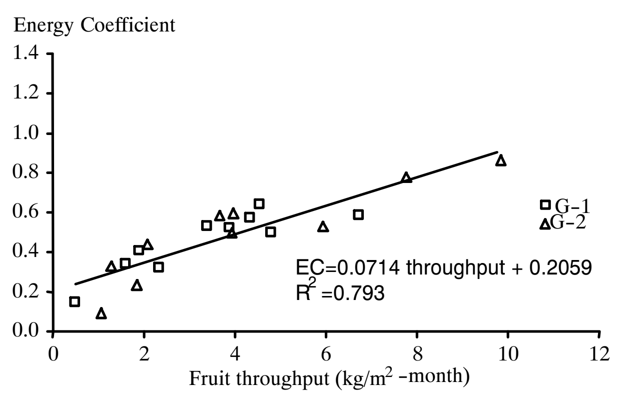

Figure 2. Effect of monthly fruit throughput on energy coefficient for two table grape forced-air cooling facilities.

Figure 3. Strawberry cold storage room with unused space.

market fruits and vegetables that were forced-air cooled (table 5) resulting in an estimated 186 million kWh of electricity use for forced-air cooling and short-term storage. This represents about 1% of total electricity use for agriculture in California (CEC, 2005).

Conclusions

Electricity use in forced-air coolers was greatest for fruit cooling, but nearly as much was used for fan operation and removing the heat they produce. Electricity for operating and cooling lights, removing heat gain through walls, and operating and cooling lift trucks comprised the next largest energy use systems in decreasing order of use. Possible methods of reducing electricity use are to utilize produce containers with adequate vent area and minimum amounts of internal packaging material. Lighting electricity use may be reduced by switching to more efficient light sources, turning lights off when people are not present, and incorporating task lighting on forklifts.

Energy efficiency was measured by an energy coefficient, an index accounting for cooling work accomplished divided by electricity purchased. The average EC for the forced-air fruit cooling facilities was the same as measured 20 years earlier. A number of options were identified to improve electricity use efficiency. Increasing product throughput per unit of refrigerated area has great potential to improve efficiency.

In 2006, forced-air cooling and short-term storage of California fresh market fruits and vegetables consumed 186 million kWh of electricity, approximately 1% of the state's total electricity use for agriculture.

Table 5. Annual electricity use for forced-air cooling of California vegetables and fruits.

Commodity	2006 Production[a] (1000 MT)	Final Temp. (°C)	Adjusted Electricity Use[b] (kWh/MT)	Electricity Use (kWh/yr)
Vegetables				
Cauliflower	292	0	59	17,396,100
Honeydew melon	159	10	26	4,038,912
Watermelon	290	15	10	2,932,017
Mushrooms	52	0	59	3,080,700
Fruits				
Apples	70	0	59	4,185,000
Apricots	8	0	59	486,000
Avocados	122	7	36	4,551,805
Blueberries	5	0	59	270,000
Boysenberries	1.6	0	59	98,010
Figs, fresh	7	0	59	410,400
Grapes, table	557	0	59	33,156,000
Kiwifruit	21	0	59	1,263,600
Nectarines	198	0	59	11,772,000
Olives, fresh	21	0	39	794,880
Peaches, processed	326	0	59	19,386,000
Peaches, fresh	220	0	59	13,068,000
Pears	208	0	59	12,366,000
Plums	143	0	59	8,532,000
Raspberries	53	0	59	3,134,700
Strawberries	750	0	59	44,663,400
Total	3,504			185,585,524

[a] Based on California Dept of Food & Agriculture data http://www.cdfa.ca.gov/statistics/.
[b] Electricity use is based on cooling the product from an initial temperature of 18°C to a final temperature of 0°C. If a commodity is cooled to temperatures above 0°C the electricity use factor has been reduced proportionately.

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