ENERGY EFFICIENCY IN FRUIT STORAGE WAREHOUSES

Marcus H. Wilcox, P.E.
President, Cascade Energy Engineering
Walla Walla, WA
Mwilcox@bmi.net

ABSTRACT

In 1995, the National Agricultural Statistics Service (NASS), a division of the USDA, estimated a total Pacific Northwest fruit storage volume of 470,000,000 cubic feet at 340 individual facilities. Based on dozens of detailed energy efficiency reviews at these types of these facilities, it is estimated that fruit storage warehouses use over 600,000,000 kWh/yr of energy, or 70 MWa. The majority of this energy is used by an approximate 240,000 hp of evaporator fans, compressors, condenser fans and pumps.

The fruit storage sector presents an outstanding opportunity for energy efficiency. Refrigeration systems account for most energy use at these facilities, and potential for savings can range from 10% to over 50%. This paper will discuss the primary energy efficiency opportunities within this sector.

ENERGY USE DISTRIBUTION

Ammonia or freon-based refrigeration systems are used at most fruit storage warehouses. At facilities with no packing line, refrigeration can use 90% to 95% or more of total utility energy use. With a packing line, refrigeration energy use can range from 70% to 80% of total facility energy, with the balance required by packing lines and lighting.

Sub-System	Percent Refrig. Horsepower	Percent Refrig. Energy
Evaporators	25%	54%
Compressors	69%	41%
Condensers	6%	5%

Figure 1. HP vs. energy.

Within refrigeration, it is a common misconception to assume energy use mirrors total connected load. Consider the statistics of Figure 1. Although evaporator fans account for only one-fourth of total refrigeration system horsepower, they use well over half of refrigeration energy. This is clearly a reflection of a system configuration that is designed for peak pull-down loads. The longer CA rooms are held, the greater the fraction that evaporator fans account for.

TYPICAL ENERGY USE PROFILE

The monthly electric utility profile is easily understood by those familiar with the use patterns of a fruit storage facility. Rooms are loaded with warm field fruit in the fall, and CA rooms are sealed within days. Once field heat is pulled out and atmospheric conditions are established, energy use steadies. Throughout the spring, energy use steadily declines as CA rooms are emptied. Energy use for some facilities nearly reaches zero during summer months. Sample utility profiles for five facilities of varying size and use patterns are shown in Figure 2.

Savings for these facilities will be shown later.

REFRIGERATION ENERGY "BASICS"

When pursuing energy efficiency in fruit storage refrigeration, there are several basic guiding principles. These include:

1. Compressor Pressure Ratio
2. Compressor Part Load Operation
3. Evaporator & Condenser Fan Control Strategies

Compressor Pressure Ratio

Performance data for a typical reciprocating compressor is shown in Figure 3.

In this example, increasing suction temperature from 15 °F (28 psig) to 25 °F (39 psig) decreases compressor energy use by 19%. If condensing temperature is then reduced from 85 °F (150 psig) to 65 °F (103 psig), total savings increases to 42%. These results can be normalized for a "rule-of-thumb" improvement, as shown in Figure 4.

That is, increasing suction temperature by a degree will decrease compressor energy use by 1.9%, while decreasing condensing temperature by a degree will save 1.4%. Any reduction in compressor "lift" will reduce energy use.

Compressor Part Load Operation

Compressor part load performance plays a significant role in energy efficiency as well. Although reciprocating compressors unload relatively efficiently, screw compressors are another matter. A sample part-load curve for a screw compressor is shown in Figure 5.

As a screw compressor unloads, it becomes less efficient. The brake horsepower (BHP) per ton of refrigeration (TR) degrades. Energy efficiency solutions for this potential problem vary in complexity and completeness, as discussed later.

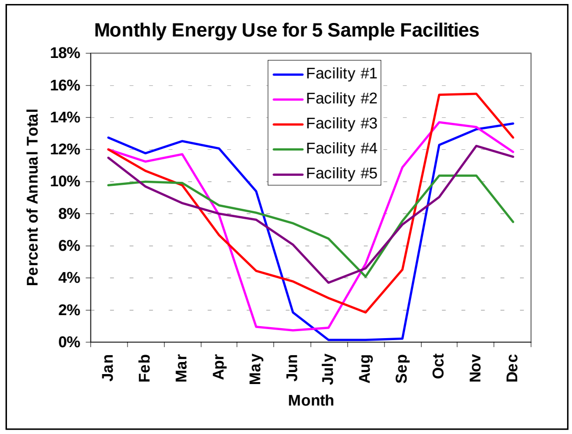

Figure 2. Monthly energy use.

Vilter 458 Compressor Performance					
Evap. Temp.	Cond. Temp.	TR	BHP	BHP/TR	Total Savings
15°F	85°F	119	131	1.10	
25°F	85°F	153	137	0.90	19%
25°F	**65°F**	165	105	0.64	42%

Figure 3. Compressor performance.

Savings from Increased Suction:	1.9% /°F
Savings from Reduced Discharge:	1.4% /°F

Figure 4. Generalized compressor savings.

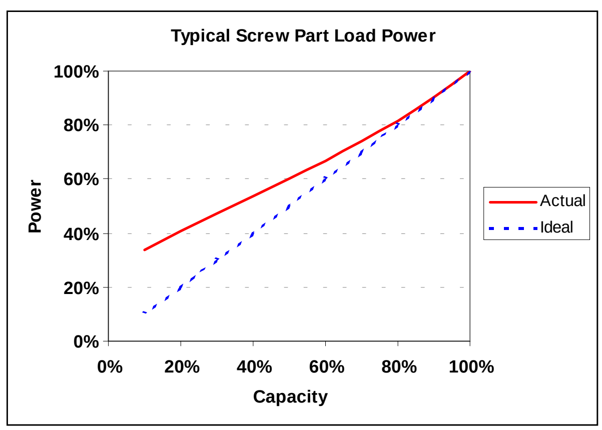

Figure 5. Screw part load.

Evaporator & Condenser Fan Control Strategies

Evaporator and condenser fans can be used for control. Under the most basic configuration, evaporator fans are operated non-stop, with the back-pressure regulator (BPR) controlling refrigerant pressure and temperature for room temperature control. Energy can be reduced by cycling evaporator fans on and off to reduce fan energy. Fan energy use becomes proportional to run time. This can be achieved through a computer control system, or manually. Some owners simply remove fuses or throw disconnects during CA holding to achieve savings.

Figure 6. Sample VFD.

Another alternative is Variable Frequency Drive (VFD) control. In general, a VFD takes the 480-Volt, 60-cycle utility power and turns it into 680-Volt DC power. The VFD then sends voltage pulses of varying width and polarity to the motor. The motor speed can be adjusted to any frequency between 0 and 60 Hz (with proper consideration for mechanical or thermal limitations of the motor and driven equipment). A sample VFD is shown in Figure 6.

The "affinity laws" predict a cubic relationship between fan speed and shaft horsepower. This means that at 50% fan speed, we achieve 50% air movement with only $50\%^3$, or 12.5% power. The real-life value is an exponent of 2.5 to 2.7, reducing electrical input power to the range of 15% to 18% at half speed. (Note that any reduction in evaporator fan power reduces the heat load to be removed by the compressors and condensers, providing additional savings.)

Condenser fans are usually cycled to control condenser capacity and system condensing pressure. This cycling is achieved through a computer control system, or simple Penn or Mercoid switches. Similar to evaporator fans, condenser fans follow the affinity laws, resulting in dramatic savings at reduced speed.

SPECIFIC RECOMMENDATIONS

Although each facility is unique, the following specific energy efficiency recommendations are most common:

1. Computer Control
2. Reduced Minimum Condensing Pressure
3. Evaporator Fan VFD Control
4. Condenser Fan VFD Control
5. Screw Compressor VFD Control

Each of these opportunities is discussed in some detail in the following section.

Computer Control

A refrigeration control system can be considered a "backbone" energy efficiency upgrade. Although the control system can save tremendous amounts of energy, it also provides a basis for proper control of VFDs. The control system can directly reduce energy use through evaporator fan cycling, compressor sequencing, automated suction pressure optimization, and better condensing pressure control relative to pressure switches. The control system also plays an important role in monitoring and managing room temperature and atmosphere conditions. Control system costs can vary widely, based on the size of the facility and whether or not atmosphere maintenance is required. A small system than only controls refrigeration may cost $25,000 to $40,000, while the cost for a large CA complex with atmosphere control could reach $75,000 to $100,000 or more.

Reduced Minimum Condensing Pressure

Most refrigeration systems are designed around peak refrigeration loads during peak summer conditions. However, fruit storage systems operate primarily during the fall, winter, and early spring. During this time, there are thousands of hours per year when ambient temperatures are extremely low, and refrigeration condensing pressure could operate as low as 80 psig (54 °F) to 90 psig (59 °F). Unfortunately, many systems maintain a higher condensing pressure during this period. There are several common reasons for the elevated condensing pressure:

- Screw compressor liquid injection oil cooling may not work properly below 125 to 140 psig.
- Gas pressure systems (i.e., pumper drum) may not operate correctly due to controlled-pressure receiver (CPR) pressure or other system limitations.
- A common water tank is used as a condenser sump and defrost water storage. The need (or desire) for warm defrost water necessitates an elevated condensing pressure.
- Often, an elevated condensing pressure is a "tradition". This can be the result of misconceptions about issues such as screw compressor volume ratios.

Each of these barriers has a solution. Whether retrofitting a screw compressor with thermosiphon oil cooling, or installing separate tanks for condenser water and defrost water, there is rarely an insurmountable barrier to achieving 80 to 90 psig minimum condensing pressure.

Evaporator Fan VFD Control

Evaporator fan VFD control is typically the single greatest opportunity to reduce refrigeration energy use. In a CA facility, fans are typically operated at full speed for several weeks following room seal. At that point, fan speed can be immediately reduced to 50%, or can be staged down over several weeks, again with a minimum of 50% speed. *(There is little incentive to reduce speed below 50% speed, since power has already been reduced by over 80%, and additional speed reduction only diminishes airflow in the room).*

In general, one VFD is installed for each CA room. Where VFDs are installed on common storages, one VFD is installed per refrigeration zone. It is important that the VFD be correctly sized and applied, as this particular application is challenging for those unfamiliar with evaporator applications. Issues of harmonics and motor protection require specification of appropriate input reactors, output dV/dt filters, and inverter-rated motors for a successful and reliable application.

A computer control system will require modification, with additional output modules, software algorithms and interface modifications to manage the VFDs.

It is also possible to install evaporator fan VFDs without a computer control system. In the simplest CA configuration, the VFD can be operated manually. Following room pull down, fan speed is manually reduced by the operator. A more sophisticated method of control involves "piggy-backing" the VFD onto the existing 4-20 mA control signal for the BPR. In fact, the common Honeywell UDC 3300 controller can be configured with a second 4-20 mA output that can be configured to manage the VFD in parallel with the standard output used for BPR control.

One benefit of evaporator fan VFD control is smooth temperature control. Although conventional fan cycling saves energy and has been shown to have no negligible effect on fruit temperature or quality, there is an inherent room air temperature swing when using fan cycling. A comparison of room air temperature with cycling and VFD control is shown in Figure 7. With sensitive qualification for foreign markets, VFDs may be a preferable alternative approach to energy savings.

Condenser Fan VFD Control

Rather than cycling condenser fans for capacity control, VFD control can be utilized. Similar to evaporator fans, the affinity laws provide excellent savings relative to simple cycling. However, a second convincing benefit also plays a part in the decision to utilized speed control.

Consider the sample 24-hour condensing pressure profile in Figure 8.

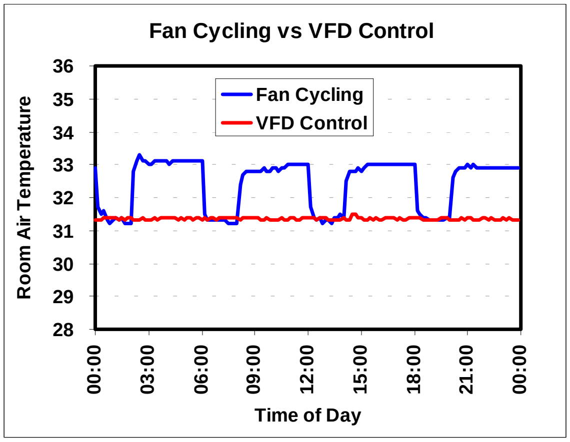

Figure 7. Cycling vs. VFD control.

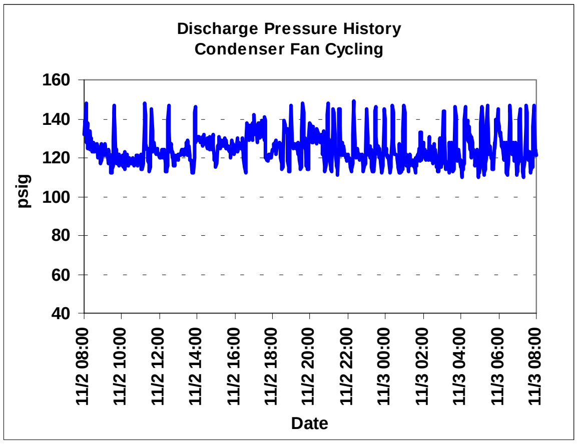

Figure 8. Condenser fan cycling.

Now, examine the pressure profile of the same system with VFD control on the condenser fans in Figure 9.

VFD control eliminates the rapid cycling of the condenser fan required for proper pressure control. With the VFD, average condensing pressure is smoother and lower. Since lower condensing pressure reduces compressor energy use, condenser fan VFDs often achieve compressor energy savings that is larger than the fan energy savings! Condenser belt and sheave wear is also reduced as a result of VFD control.

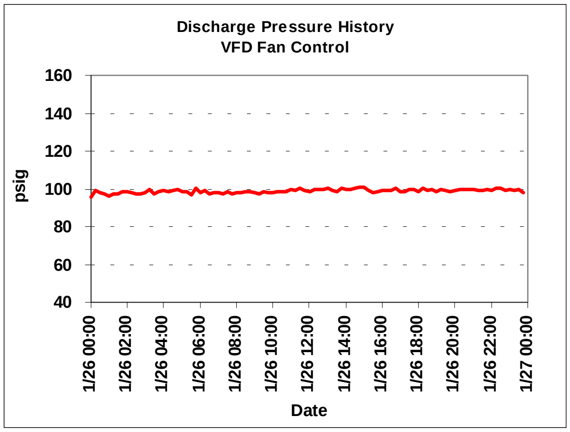

Figure 9. Condenser VFD control.

Screw Compressor VFD Control

Often, operating a screw compressor unloaded can be avoided by a diverse selection of machines that can be properly sequenced by the control system. In other systems, reciprocating compressors are used to efficiently trim system capacity and power. However, in some systems, there is no avoiding operation of a screw compressor in the unloaded condition.

In this situation, a VFD can be installed for the screw compressor. Rather than using the conventional slide valve for unloading, the compressor speed is reduced from 3600 to 1800 rpm, keeping the slide valve fully open. Once at 1800 rpm, the slide valve is then closed to further reduce capacity. The improved part load power curve is shown in Figure 10.

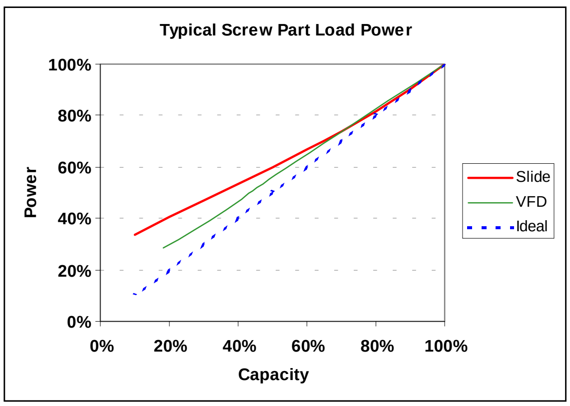

Figure 10. Compressor VFD control.

Note that the effectiveness of compressor VFD control is dependent on a variety of issues, including the shape of the basic compressor part load power curve. However, there are certainly times when this VFD application is viable.

NEW CONSTRUCTION OPPORTUNITIES

New construction projects present several additional opportunities for refrigeration energy efficiency. These include:

- **High-Efficiency Condensers:** Condensers are selected with heat rejection per horsepower ratings of 300 MBH/hp or higher.
- **Larger Condensers:** Condensers are selected at lower design condensing temperature (e.g., 85 °F rather than 95 °F), saving both compressor and condenser energy.

- **Diverse Compressors:** Rather than a few large compressors, a diverse selection of machines can be made to allow for optimum sequencing. This helps avoid operating screw compressors unloaded. A combination of screw compressors (for harvest) and reciprocating compressors (holding season) can be beneficial.
- **Incremental Cost for VFDs:** On new construction projects, the cost of VFD control is tempered by savings from eliminated magnetic starters. VFD cost can be as much as 20% to 50% lower during new construction.
- **Premium Efficiency Motors:** Upgrading to premium efficiency motors may be viable for some loads. Condenser pumps and holding-season compressors are two examples.

OTHER EFFICIENCY OPPORTUNITIES

Two non-refrigeration opportunities are commonly encountered with fruit storage warehouses: lighting upgrades and fast-acting doors.

Lighting Upgrades

In general, lighting can be upgraded in packing warehouses and common storages. In packing areas, standard fluorescent lighting can be upgraded to electronic ballasts and T8 or T10 lamp technology. Obviously, any incandescent lighting should be retrofit with fluorescent or metal halide technology.

In common storages, metal halide light fixtures can be installed (or retrofit) with bi-level lighting. A single fixture or group of fixtures is controlled by a motion detector. When no activity is seen for 5 to 15 minutes, the fixture dims. When dimmed, a 400-Watt metal halide fixture that normally draws 465 input Watts may only draw 180 to 200 Watts. When a lift truck or other motion is detected, the fixture immediately increases light output, with none of the delay common to initial startup of metal halide and other high-intensity discharge fixtures.

Fast-Acting Doors

Common storages are notorious for significant infiltration loads. Doors are often left open, or strip curtains are damaged to the point of reduced effectiveness. In some situations, an automated, fast-acting door can be installed to reduced infiltration load. Reducing infiltration can benefit evaporator fan VFDs or fan cycling by reducing room load.

CASE STUDIES

Five fruit storage warehouses were chosen as examples for this paper (Figure 11). The range in size from 193 to 1,448 hp of refrigeration. Annual energy use ranges from 618,000 to 4,099,000 kWh/yr. Savings ranges from 21% to 47% of total facility energy use. Simple payback ranged from 3 to 6 years without utility incentives, and 1.5 to 3.1 years with utility incentives.

FRUIT WAREHOUSE ENERGY EFFICIENCY CASE STUDIES

Case Study:	**#1**	**#2**	**#3**	**#4**	**#5**
Refrigeration Horsepower:	277	193	976	777	1448
Rooms (Common & CA):	4	3	25	19	24
Total Facility Energy (kWh/yr):	618,400	713,600	1,641,300	2,114,260	4,098,880
Refrigeration Energy (kWh/yr):	595,976	510,599	1,625,757	1,676,594	3,734,135
Refrigeration Percentage:	96%	72%	99%	79%	91%

Computer Control					X
Reduced Condensing Pressure	X	X	X	X	X
Evaporator Fan VFD Control	X	X	X	X	X
Condenser FanVFD Control	X	X	X	X	X
Lighting Upgrades		X			
Miscellaneous			X		

Energy Savings (kWh/yr):	290,245	333,080	661,225	892,894	879,489
Percent Savings of Total Facility:	47%	47%	40%	42%	21%
Cost Savings ($/yr):	$ 9,683	$ 12,939	$ 24,227	$ 30,555	$ 30,791
Installation Cost:	$ 29,349	$ 80,504	$ 118,251	$ 112,894	$ 152,515
Simple Payback (years):	3.0	6.2	4.9	3.7	5.0

Utility Incentive ($0.12/kWh, up to 50%):	$ 14,675	$ 39,970	$ 59,126	$ 56,447	$ 76,258
Final Customer Cost:	$ 14,675	$ 40,534	$ 59,126	$ 56,447	$ 76,258
Simple Payback After Incentive (years):	1.5	3.1	2.4	1.8	2.5

Figure 11. Fruit warehouse case studies.