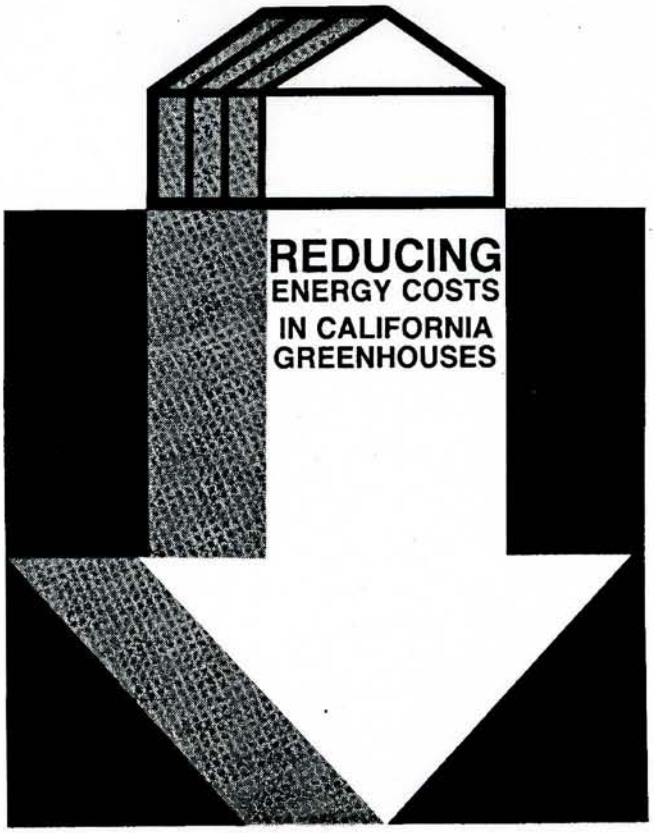


INTRODUCTION

The California greenhouse culture of cut flowers, potted plants, and vegetables grossed about $400 million at the farm gate in 1981 from an estimated 3,000 acres of greenhouses in 23 counties. California's greenhouses use an average of 1.15 therms (1000,000 Btu's per therm) of natural gas for each square foot of floor area, and this represents about 13 percent of all natural gas used in California agriculture. Electricity use averages about 1.10 kilowatt hour per square foot of greenhouse floor area. Utility costs for commercial California greenhouses in 1981 represented over 19 percent of the estimated farm gate value of production.

Between 1977 and 1982, natural gas prices increased about 160 percent and electricity prices increased 68 percent. Energy costs for commercial California greenhouses averaged over 60 cents per square foot of greenhouse floor area at June 1982 utility rates, for a total industry cost of over $100 million.

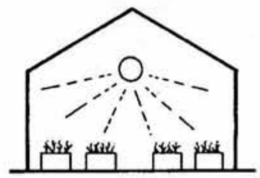
A greenhouse owner or manager has four options for reducing high energy costs. The choice is not which of the following options to use, but rather in which order.

- Reduce greenhouse heat losses.
- Increase efficiency of heating and cooling systems.
- Change management practices and crop mixes.
- Reduce fuel costs with alternate energy sources.

This bulletin describes a wide variety of methods useful for reducing utility bills; however, not all are appropriate for every greenhouse or greenhouse operation. Costs associated with most of the suggested actions may range from 2 cents to more than $1.00 per square foot of floor area. Expected energy savings also vary from 5 to 50 percent or more, and not necessarily in relation to initial costs. Many energy cost-reduction actions for greenhouses qualify for an investment tax credit; some qualify for additional Federal and State energy tax credits. Selecting appropriate actions to reduce energy costs for greenhouses involves many important considerations, and each greenhouse and management system has special needs.

Many commercial California greenhouse operators have reduced energy expense by 50 percent or more within the last 2 years, and at nominal and economical costs, by judicious use of some of the actions suggested in this bulletin. These actions and expected energy savings are described in Sections I through IV. Section V provides current costs of various actions, payback time, and other economic guidelines to help you select energy-saving actions best suited to your operation. **There is no better time than now to prepare a plan of action.**

SECTION I



REDUCE GREENHOUSE HEAT LOSSES

How heat is lost

Understanding the basic methods of heat loss from a greenhouse allows you to evaluate the usefulness of energy conservation methods for your own greenhouse. The movement of heat energy into, out of, or within a greenhouse takes place by one or more heat transfer processes: conduction, convection, radiation, and evaporation.

Conduction. Accounting for the largest heat loss in a greenhouse, conduction is the movement of heat through the covering and soil to the cool outside. The rate of conduction heat transfer is proportional to the difference between the inside and outside temperatures, the insulating ability of the greenhouse cover, and the total surface area of the covering. This is expressed by the following equation:

$$Q = UA\ (t_1 - t_2)$$

Where: Q = conduction heat transfer rate, Btu/hr

U = heat transfer coefficient, Btu/hr·ft^2·°F (Note: $1/U = R$; R is the common number used to rate insulation)

A = surface area, ft^2

$t_1 - t_2$ = inside temperature minus outside temperature, °F.

In greenhouses, we are mainly interested in the loss of heat by conduction through walls or roof surfaces. The U-value of a single polyethylene wall is 1.15 Btu/hr·ft^2·°F (table 1). A double inflated polyethylene wall (table 1) has a U-value of 0.70 Btu/hr·ft^2·°F. A second layer of polyethylene on a greenhouse wall reduces heat loss by 39 percent. Greenhouse wall and roof materials should have the smallest U-value, or the largest R-value, and still allow sufficient light for production.

Convection. Heat transfer within a greenhouse is caused by air at one temperature moving past a surface or object at a different temperature. An example of convection is the loss of heat from warm greenhouse air to a cold outside wall as air circulates past the wall. If the inside of the wall is warmed by moving air, the temperature of the inside wall surface increases compared to a wall with still air next to it, increasing heat conduction across the wall. Much of the heat of an overhead steam line is transferred by convection to air moving across it; the remainder is radiated heat.

TABLE 1. Suggested heat loss rates and infiltration rates to use in greenhouse heat loss calculations

Materials	Heat loss rates U-values (Btu/hr·ft^2·°F)	Infiltration rates A_c (Air changes/hr)
Single poly*	1.15	0.80
Glass†	1.13	1.50
FRP	1.00	1.00
Double-wall panels‡	0.68	0.80
Double inflated poly§	0.70	0.70
Glass + single poly layer‖	0.75	0.70
Glass + double poly layer#	0.50	0.60
FRP + single poly layer‖	0.75	0.60
Drop single poly walls**	1.15	2.00
Rigid insulation, 1 inch††	0.14	0.30
With thermal blanket		
• Single poly, glass, FRP roof		
Clear poly blanket	0.65	0.50
Porous blanket	0.60	0.60
Solid blanket	0.50	0.50
• Double poly roof#	0.40	0.30
• Double-wall panel roof#	0.40	0.40

* "POLY" indicates plastic films—polyethylene, vinyl, etc.
† Infiltration varies from 1 (good condition) to 4 (leaky, poor condition).
‡ Twin-wall rigid panels of acrylic, polycarbonate, or polypropylene.
§ Inflate, or a double layer enclosing an air space.
‖ Film underneath, with an air space.
\# Double, inflated polyethylene over glass.
** Typically used in California transplant greenhouses.
†† Rigid board—styrofoam, polyurethane, isocyanurate, etc.
‡‡ With solid blanket.

There is a convection heat transfer coefficient comparable to the U-value in the conduction equation. However, this is difficult to determine and to use, and we normally do not make, or need, any convection heat transfer calculations. Remember, convection heat transfer is strongly related to air velocity, and increases rapidly as the velocity of air (past a surface) increases. Convection transfer can be minimized by placing barriers in the path of air flow to reduce the movement of air. Providing a "dead" air space is the basis for some methods of insulating —as with a double layer of polyethylene, for example.

A form of convection exchange also occurs when cold outside air mixes with warm greenhouse air due to controlled ventilation or to infiltration (the natural movement of air through cracks and openings in the greenhouse).

Radiation. Heat exchange occurs when an object is at a different temperature than its surroundings. An object radiates heat to colder surroundings and gains heat from warmer surroundings. Heat radiation is much like light, it travels in a straight line and is not affected by air movement. Air is not heated by radiation. The sun warms the ground by radiation but not the air; air is warmed by convection as it moves over the heated ground. A greenhouse both gains and loses heat by radiation. It gains heat during the day by radiation from the sun. At night, plants and other objects radiate heat to the cool sky above them. Greenhouse coverings vary in their ability to retard movement of radiant heat. Glass allows very little exchange of radiant heat between warm plants and a cold sky; however, a polyethylene film will allow most radiant heat to pass through. These characteristics will be discussed in a later section.

Evaporation. Vaporization or evaporation occurs when water changes from a liquid to a gas; the gas then becomes mixed with air and humidifies it. Evaporation requires energy, about 1,050 Btu per pound of water. A greenhouse has nearly a continuous exchange of heat by evaporation. Condensation is the reverse of evaporation. Each pound of water that condenses on the inside of a greenhouse releases 1,050 Btu of heat.

When plants give off moisture, they also lose heat. Moisture, through the processes of evaporation and condensation, plays an important role in the movement of heat within the greenhouse.

Calculating heat losses

Heat loss from a greenhouse, other than by infiltration, occurs mostly by the heat conduction across the surface enclosing the greenhouse. As mentioned, the driving force for this exchange of heat is the difference in temperature between the two sides of the enclosing surface; the greater the temperature difference the greater the rate of heat transfer.

The two surface temperatures are controlled by other forms of transfer. The outside greenhouse surface, for example, is convectively cooled or warmed by wind blowing across it. The inside surface temperature is affected by convection as inside greenhouse air moves across it, by moisture condensing on the surface (adding heat to it) evaporating from it (withdrawing heat), or by radiation heat exchange (for example, radiation from steam lines to the roof surface).

This mixture of processes makes exact calculations of greenhouse heat losses difficult. But we can make good estimates by treating the losses as if all were by conduction and using U-values that account for the mixture of heat transfer processes. Table 1 lists the U-values for various greenhouse conditions.

In addition, *infiltration heat loss* must be accounted for. You might think of this as warm air loss through cracks and around doors and ventilators. Such heat losses can be substantial, accounting for as much as 10 to 20 percent of the total. Infiltration heat losses are determined by,

$$I = 0.02\, A_c \times V \times (t_1\text{-}t_2)$$

Where: I = infiltration heat exchange, Btu/hr

A_c = air exchange rate, exchanges per hour

V = volume of greenhouse, ft^3

$t_1\text{-}t_2$ = temperature difference between inside and outside air.

The air exchange rate, A_c, is an estimate of how many times per hour the entire air volume of the greenhouse is exchanged by infiltration. Experimentation and practice have provided estimates of A_c for various greenhouse coverings (table 1).

When working with heat losses from a greenhouse, it is helpful to determine an overall *heat loss factor* for the greenhouse. This loss has the same dimensions as the insulation U-values used for individual building components (Btu/hr per °F per ft^2) of greehhouse floor area. This is done by letting the air temperature difference, $t_1\text{-}t_2$, be equal to one in the heat loss formulas. This allows us to easily determine the total greenhouse heat requirement for any set of air temperature conditions by,

$$\text{Heat requirement (Btu/hr)} = \text{heat loss factor} \times (t_1\text{-}t_2) \times \text{greenhouse floor area.}$$

We can compare the value of various greenhouse insulating treatments by comparing heat loss factors (see table 3). Follow the example calculation to determine heat losses (or heating requirements) for any greenhouse.

Example calculation

Assume that we want to determine the heat loss or heating requirement of a gutter-connected, gable-roof range covered with a single layer of polyethylene, and to compare this heating requirement with the same greenhouse range covered with a double-inflated layer of polyethylene. Assume a range of 16 gutter-connected houses, each 30 by 210 feet, with dimensions as shown in tables 2 and 3, where:

$N = 16$, number of houses

$A = 10$ ft, gutter height

$B = 6$ ft, gutter to ridge distance

$C = 30$ ft, width of one house

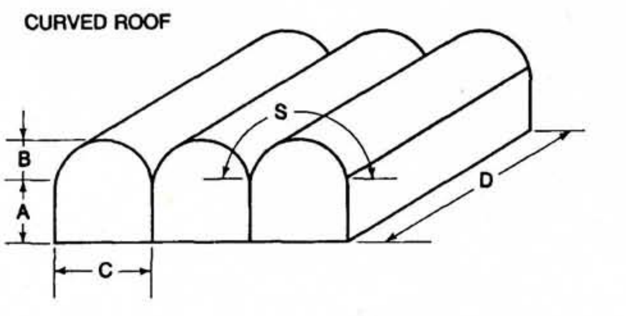
$D = 210$ ft, length.

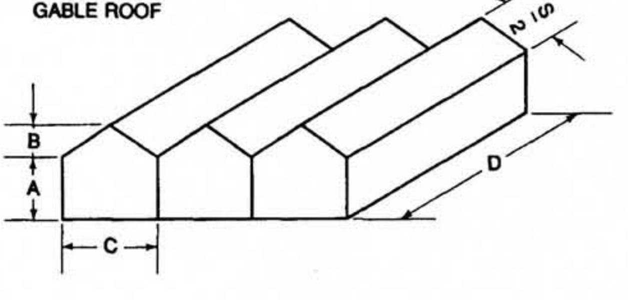
TABLE 2. Formulas to use in calculating greenhouse heat losses

Item	Gable roof	Curved roof
Wall area, ft^2	$2A[NC + D]$	$2A[NC + D]$
Gable area, ft^2	NBC	$\frac{4}{3}NBC$
Roof area, ft^2	$ND[4B^2 + C^2]^{1/2}$	$\frac{ND[4(4B^2 + C^2)^{1/2} - C]}{3}$
Volume, ft^3	$NCD[A + \frac{B}{2}]$	$NCD[A + \frac{2B}{3}]$
Perimeter, ft	$2[NC + D]$	$2[ND + D]$
Floor area, ft^2	NCD	NCD
Roof width, ft	$(4B^2 + C^2)^{1/2}$	$\frac{4(4B^2 + C^2)^{1/2} - C}{3}$

Note: For a single, free-standing house, $N = 1$.

Measurements showing greenhouse structures used in table 2 are shown in the following drawing.



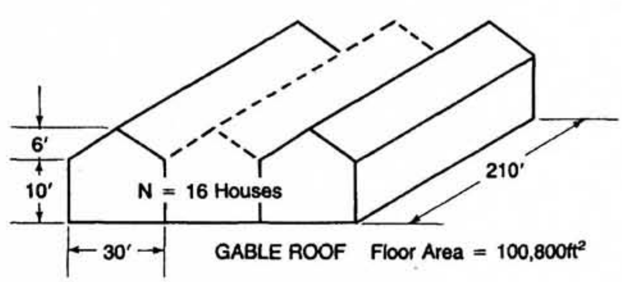


Insulation treatments are shown in table 3.

TABLE 3. Overall heat loss from example greenhouse ($100{,}800\ ft^2$) with various roof and wall materials, and insulation treatments

Material: Roof	Material: Walls	Overall heat loss ($Btu/hr \cdot ft^2 \cdot °F$)
Single poly	Single poly	1.64
Single poly	Poly drop walls	1.70
Glass	Glass	1.79
FRP (fiberglass)	FRP	1.50
Glass + single poly	Glass	1.20
Glass + single poly	Glass + single poly	1.11
FRP + single poly	FRP	1.14
FRP + single poly	FRP + single poly	1.09
Double poly	Single poly	1.13
Double poly	FRP	1.11
Double poly	Double poly	1.05
Double-wall panels	Double-wall panels	1.05
Insulation: Blanket on roof and walls		
Clear—single poly, glass or FRP		1.01
Porous—single poly, glass or FRP		0.98
Solid—single poly, glass or FRP		0.85
Solid—double poly		0.63
Solid—double panels		0.65
Insulation: 1 inch poly (R-7) on east and north walls		
Single poly		1.54
Glass		1.69
FRP		1.42

Measurements of the greenhouse used in table 3 are shown in the following drawing.



For a single layer of polyethylene the U-value is 1.15 $Btu/hr \cdot ft^2 \cdot °F$ and A_c is 0.80 air changes per hour (table 1); for a double-inflated layer of polyethylene the U-value is 0.70 $Btu/hr \cdot ft^2 \cdot °F$ and A_c is 0.70 air changes per hour. Use these values, along with the areas and volumes determined from the formulas of table 2, in the conduction and infiltration heat loss equations. The results of the calculations are shown in the following chart.

		Heat loss, Btu/hr·°F	
		Single poly house	Double poly house
		$U = 1.15$	$U = 0.70$
		$A_c = 0.80$	$A_c = 0.70$
		$t_1\text{-}t_2 = 1$	$t_1\text{-}t_2 = 1$
Conduction:	$Q = UA(t_1\text{-}t_2)$		
(area)	(ft^2)		
Walls	13,800	15,870	9,960
Gable	2,880	3,312	2,016
Roof	108,564	124,849	75,994
Infiltration:			
	(ft^3)		
Volume	1,310,400		
$I = 0.02\ A_c \times \text{Vol} \times (t_1\text{-}t_2)$		20,966	18,346
Total heat loss, Btu/hr·°F		164,997	106,016
Heat loss factor, Btu/hr·ft²·°F		1.64	1.05

Several important observations can be made from this example:

(1) Greenhouse heat loss, as measured by Btu/hr·°F, can be used to determine the heat required to maintain a desired inside temperature at some design outside temperature. For the single poly house whose heat loss is 164,997 Btu/hr·°F, the heating system would have to supply nearly 5 million Btu/hr to maintain an inside temperature of 60°F when it was 30°F outside (164,997 Btu/hr·°F·30°F). With double poly we would need only about 3 million Btu/hr. Also, given a heating system with a known hourly Btu output, we can divide this figure by the calculated heat loss rate (Btu/hr·°F) and determine the maximum temperature difference for which the system will provide adequate heat.

(2) Notice that 75 percent of the total heat loss is from the roof of the single poly house. Infiltration loss is about 12 percent of the total. The example calculation can be useful in understanding where the greatest heat losses occur and where these heat losses can be reduced.

(3) The overall heat loss factor is an easy number to use when comparing total greenhouse heat losses. The example calculation shows that the additional layer of polyethylene will reduce the heating requirement about 36 percent [(1.64-1.05)/1.64].

Any greenhouse coverings or treatments can be compared in this manner. Comparisons were made for the example greenhouse and the results are listed in table 3.

The size and shape of the greenhouse for which the heat loss calculations were made is quite typical for many commercial ranges. To determine heating requirements for a similar greenhouse, select an overall heat loss value from table 3 and multiply by the greenhouse floor area and the temperature difference the heating system needs to maintain. The value of various wall and roof treatments, thermal blankets, and other methods of insulating for greenhouse energy conservation will be discussed in a later section.

Methods of insulating and reducing infiltration

Insulating the greenhouse is one of the most economically effective methods available to conserve energy. Fortunately California growers have more options for insulating than do growers in colder climates where snow and prolonged cold must be considered.

Table 4 lists some methods used and resulting typical energy reductions in California greenhouses. All reductions, however, are not additive.

TABLE 4. Insulating a greenhouse

Method	Expected energy use reduction (%)
Inner layer of poly: on roof	25
on walls	10
on roof and walls	35
Permanent polyethylene subroof	20-30
Part. permanent subroof	25
Thermal blankets	35-57
Double inflated polyethylene over glass	25-45
Double inflated polyethylene to replace FRP or single polyethylene	30-40
Single polyethylene over FRP or glass	25-35
Ridge vent insulation	5-10
Wall insulation	5-10
Seal glass laps	up to 10
Polyethylene tubes to close sides or vents	up to 20
Polyethylene tubes to cover evaporative pads	up to 20

Table 5 shows the distribution of heat losses from a typical, unmodified, large, California greenhouse range of glass, fiberglass, or single-layer polyethylene. More heat is lost through the roof than any other area.

TABLE 5. Heat losses in typical California greenhouse ranges

Area	Heat loss (%)
Walls	9
Gable ends	2
Roof	68
Method	
Infiltration	21

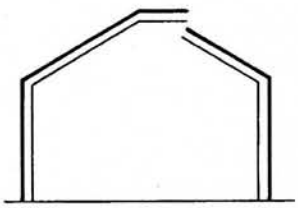
Losses can be reduced primarily through materials used, and by insulating in a manner that will not reduce light to a detrimental level. Infiltration (air leakage) is the next big source of heat loss. Each of the actions are discussed later, along with costs. All suggested costs shown are per square foot of greenhouse floor area unless otherwise noted.

Inner layer of polyethylene

Inside of roof: (plan for 18¢/ft^2 initially—8¢/ft^2 to replace after 3 years.)

Inside of walls: (plan for 2¢/ft^2 initially—1¢/ft^2 to replace after 3 years.)

All of inside: (plan for 20¢/ft^2 initially—9¢/ft^2 to replace after 3 years.)



- Use poly, vinyl, air cell, etc.
- Permanent
- Good under glass
- Watch light under fiberglass
- SAVE: 25% on roof
  10% on walls
  35% on both

Adding an insulating air space to the walls or roof is one of the most practical and cost-effective methods of conserving energy in a greenhouse. This can be done by adding an inner lining of a clear, light-transmitting material, such as clear polyethylene or other film, or clear air-cell-type material. It's a good energy conservation practice to provide a stagnant (nonmoving) layer of air next to any outer greenhouse surfaces. The layer of air formed by the outer greenhouse surface and inner lining should move as little as possible; less movement means a better insulating value and less conduction heat loss. Therefore, any layer of material added to outer greenhouse surfaces should form a tight closure. A tightly sealed layer will also reduce air infiltration. If your plants have a high light requirement, try this in a small section of your greenhouse to determine its effect on plant growth and quality. If polyethylene film is used, 6-mil is recommended because it is mechanically stronger than thinner materials and should last at least 4 years. The inner layer does not need to be UV-resistant (treated to resist degradation by ultraviolet light) because the top layer will screen out most of the ultraviolet light.

The added roof layer will probably reduce light in the greenhouse about 10 percent. This method of energy conservation has short payback periods, assuming the reduced light does not affect plant production. An insulating layer on the walls will payback the first year, on the roof it will payback the second year, and covering all of the inside of the greenhouse will payback in the second year. The insulating layer will reduce heat loss about 25 percent when added to the roof, about 10 percent when added to greenhouse walls, for a total heat loss reduction of about 35 percent if added to all outer greenhouse surfaces.

Permanent polyethylene subroof

(plan for 15¢/ft^2 initially—7¢/ft^2 to replace)

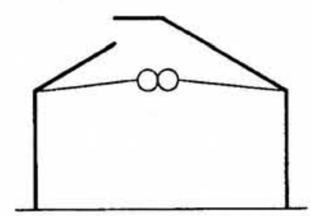
- Use clear 6-mil poly
- Heating system must be below subroof
- Ridge vents not used
- Light will be reduced 10%
- SAVE: 20-30%

A permanent subroof of a light-transmitting material such as clear polyethylene will economically reduce heat loss by 20 to 30 percent. It provides a stagnant insulating air layer below the roof, reduces heating and cooling volume, and reduces infiltration heat losses. The greenhouse should not use a ridge vent, and any heating system must be below the subroof. A subroof will reduce light levels by 10 percent or more and can be a problem in some areas for some plants.

Low-cost, plastic, poly locking strips are suggested for fastening poly films inside a greenhouse. The higher initial and installation costs for locking strips (versus lath battens) will reduce later replacement labor costs and will result in a better-fitting, more energy-efficient installation.

Partial permanent subroof with tubes

(plan for 19¢/ft^2 initially—10¢/ft^2 to replace)

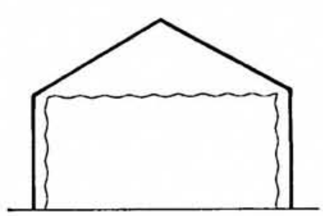


- Can be used with ridge ventilation
- Use clear 6-mil poly
- Heat must be below subroof
- Light will be reduced 10%
- SAVE: 20-30%

If greenhouse ridge vents are used for ventilation, a partial, permanent subroof of clear film can be combined with an inflatable poly tube that will close the subroof. When deflated, the tubes allow daytime use of the roof vents. This should reduce energy use about 25 percent. One California grower reported energy savings of 45 percent for foliage plant production. This type of subroof will also reduce light about 10 percent.

Thermal blankets

(plan for $1.00/ft^2 installed)



- Heating system must be below blanket
- Use poly tubes, clear 4-mil poly, black 4-mil poly, combinations of clear and opaque, other materials like Foylon, Tyvek, Thermoshade
- SAVE: Single blanket 38-75%
  Double blanket 60-80%
  Insulated blanket 80% plus

There are several thermal blanket installations in California greenhouses and they are reducing energy use by 35 to 48 percent. The blankets, when pulled at night, reduce the heated volume of the greenhouse, reduce the circulation of heated air past cool roof surfaces, and reduce heat loss that normally occurs when warm plants and soil radiate heat to the cool, outside shell of the greenhouse.

The cost and effectiveness of the blankets depends on the support system, the blanket material, and the quality of the installation.

Support system. Most thermal blankets slide or hang on metal or plastic wires. A hung system is generally more costly than a sliding system but will last longer since there is no sliding wear on the fabric. Older greenhouses have experienced excessive stress on structural members supporting the wires. Many newer greenhouses have grooved truss members designed to support hung blanket systems.

Blanket material. A wide variety of blanket material is available. *Solid opaque* material costs as little as 2 cents per square foot for a laminated material, usually with one or more reflective surfaces. A solid opaque material is best for reducing heat loss but unless sloped, tends to collect and "pocket" condensation from cold roof surfaces. *Solid clear* material such as polyethylene or vinyl costs 3 to 7 cents per square foot. They also tend to collect condensed moisture, but some growers prefer working by early morning light while the blanket is still closed. Some growers punch small holes in solid materials to allow moisture to move through. *Porous blankets* are preferred by many California growers because condensed moisture can move through them. Porous blanket materials vary in the amount of light they let into the greenhouse. Some can be used for summer shading (insulation effectiveness is reduced with increasing transparency).

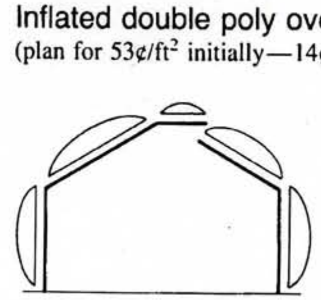
Some double-blanket systems have been installed using a solid opaque material above a porous (semitransparent) material. Such a combination will reduce heat loss (both blankets closed), provide photoperiod control (opaque blanket closed), and provide summer shade (porous blanket closed).

Blanket location. Blankets can be installed to pull from gutter-to-gutter or from truss-to-truss. A gutter-to-gutter installation provides the smallest heating volume but is often impractical because of an overhead heating system, or the need for overhead production space for hanging plants.

Quality of installation. The blanket system should prevent air movement from below the blanket to above it. A good quality installation will have tight closures where curtains meet at gutters or where the curtain meets the wall.

Inflated double poly over glass

(plan for 53¢/ft^2 initially—14¢/ft^2 to replace)

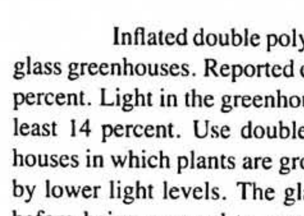


- 6-mil top—4-mil under
- Light can be reduced 14% or more
- Glass should be clean
- SAVE: 24-45%

Inflated double poly roofs have been added to existing glass greenhouses. Reported energy savings have been about 45 percent. Light in the greenhouse will probably be reduced by at least 14 percent. Use double poly over glass only for greenhouses in which plants are grown that are not seriously affected by lower light levels. The glass should be thoroughly cleaned before being covered to maximize light transmission. A poly "bubble" should be less than 100 feet long and less than 18 to 20 feet wide. Check with your plastic film supplier for maximum spans for inflated double poly roofs for safe structural pressures. Usually, one, 1/30 horse-power blower is recommended for each 10,000 square feet of roof area. A blower should provide 0.2 to 0.5 inch of water static pressure with a layer maximum separation of 16 to 24 inches. The 0.5 inch static pressure will help prevent the plastic from flapping under high wind conditions.

Inflated double poly to replace FRP or single poly

(plan for 36¢/ft^2 initially—14¢/ft^2 to replace)

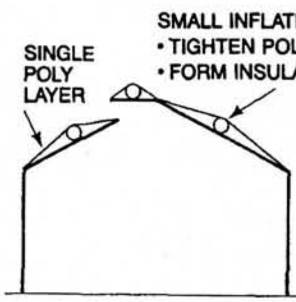


- 6-mil top—1-mil under
- Light can be reduced 10%
- Available: Polyethylene, polyester, polyvinyl, Tedlar, Teflon, other new films from DuPont
- SAVE: 30% replacing FRP
  38-40% replacing glass or single poly

Inflated double polyethylene roofs are a good energy-saving replacement for single poly or fiberglass roofs, if some light reduction can be tolerated. Double poly replacement glass or a single layer of polyethylene film will reduce energy use 38 to 40 percent. Double poly will reduce energy use about 30 percent if used to replace a fiberglass roof. Light will be reduced about 10 percent under double poly compared to glass or a single layer of poly. Light transmission of new fiberglass is more diffused, which is preferred for some crops by some growers. A "poly" roof generally means polyethylene film, but there are also good commercial nonpolyethylene films available, such as polyvinyl, polyester, and some combinations of these. The DuPont Company is testing Tedlar films in a California greenhouse as a double inflated roof. Several other films are under development by the DuPont Company. Some will be relatively expensive (in the range of 16¢/ft²) but they are reported to retain good light transmission and to have a potential life of 20 years or more.

Single polyethylene over FRP or glass

(plan for 48¢/ft² initially—10¢/ft² to replace)



- If light under double poly is unacceptable
- Use for roof or endwalls over glass or FRP
- Use 18-inch diameter poly tubes
- SAVE: 25-35%

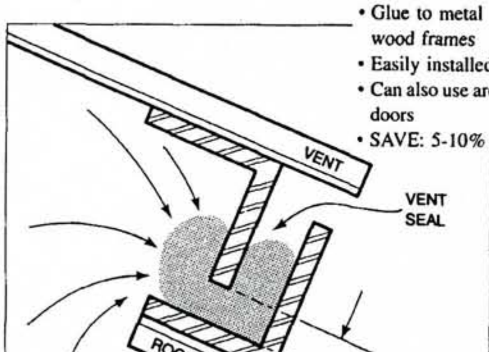
A single layer of polyethylene over glass or fiberglass has been successfully used in California. It should reduce energy usage 25 to 35 percent. A single-layer polyethylene film over an existing glass or fiberglass roof can reduce energy use about 34 percent over glass and about 25 percent over fiberglass. The addition of a single layer of polyethylene is probably more cost effective for most California greenhouses than adding a double layer. The 10 to 12 percent loss in light transmission, compared with glass or fiberglass is not as great as for a double poly film of about 14 percent, and energy savings are still good.

The single layer is supported by a small, nonperforated tube. The inflated tube will tighten the sheet and form an insulating air space between the poly and the existing roof. One grower used a 30-inch tube and 1/2 inch of water static pressure that resulted in a 15 inch separation between poly and glass. This worked well and withstood strong winds, but the grower believes that an 18-inch tube will be better for the next installation.

Ridge vent sealing

(plan for 2¢/ft² of greenhouse floor area)

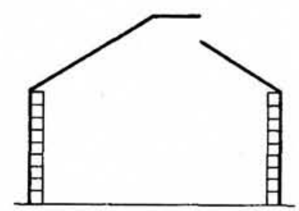
- Reduce air leakage
- Glue to metal frames, or tack to wood frames
- Easily installed
- Can also use around windows and doors
- SAVE: 5-10% plus



Ridge vents seldom close tightly, particularly on older greenhouses. Leaking vents can cause a heat loss equal to 5 to 10 percent or more of total greenhouse energy use. Good commercial sealing strips are available that can be glued to metal frames or tacked to wood frames to serve as weather stripping. This type of seal costs from 26 to 50 cents per linear foot, depending upon the type of frame to which it will be attached and the quantity purchased. For a typical California greenhouse, this amounts to only about 2 cents per square foot of greenhouse floor area. With even a 5 percent reduction in energy loss credited to it, sealing vents will payback in the first year, making them a very wise investment.

Wall insulation

(plan for 2½¢/ft² of greenhouse floor area)



- Permanent
- Use clear poly and air space, or air cell material, or rigid boards insulation on north and east walls–Thermax, etc.
- SAVE: 5-10% or more

Wall insulation can be made with an inner layer of light-transmitting material enclosing a dead air space of 3/4 inch to 1 inch thick rigid insulation boards on the north wall, and sometimes on the east wall. In metal frame greenhouses, these boards can often be cut for a pressure fit to reduce installation labor. The insulation's inside surface should be reflective or painted white to compensate for the loss of north or east wall lighting. Some growers have experienced leaf burn with reflective insulation and prefer the more diffused light produced by a white wall.

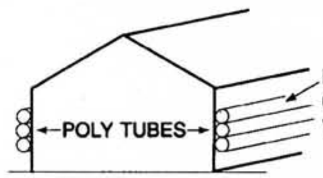
Seal glass laps

(plan for 20¢/ft² of area covered)

Sealants applied to a glass greenhouse reduce infiltration heat losses that can amount to 15 to 20 percent or more of the total greenhouse heat loss. Sealants are generally applied commercially after dirt and moisture are first blown from between glass laps. A clear silicone-based sealant is injected to fill the glass-lap space. It is nonhardening and will maintain a seal during glass expansion and contraction. It also prevents glass from slipping.

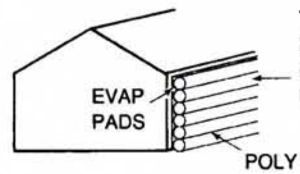
Ohio State University indicates that in their area sealing glass laps can reduce energy use 5 to 40 percent. Older glass houses with wood frames, in average or below average repair, usually realize the most savings. Ohio State University also suggests that it is usually not profitable to seal new glass greenhouses unless they were sealed during construction.

Polyethylene tubes to close sides or vents
(cost varies)



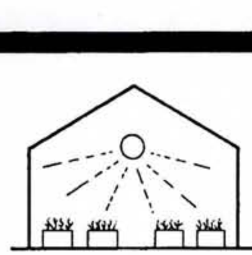
Polyethylene tubes can be used effectively to close greenhouse sidewalls or vents. Many greenhouses in warmer areas need drop sidewalls for loading and unloading the greenhouse or for ventilation. Nighttime heat loss through such closures can be excessive. Polyethylene tubes provide excellent night insulation when they are inflated to fill an open sidewall space or a vent. They can be deflated during periods when the sidewalls or vents need to be open for ventilation or for handling products.

Polyethylene tubes to cover evaporative pads
(cost varies)



Polyethylene tubes can be used to reduce infiltration and heat loss through evaporative pads where they are not in use. They are equally effective on the outside or the inside of the greenhouse, but last longer if located inside as they are not exposed to sunlight.

SECTION II



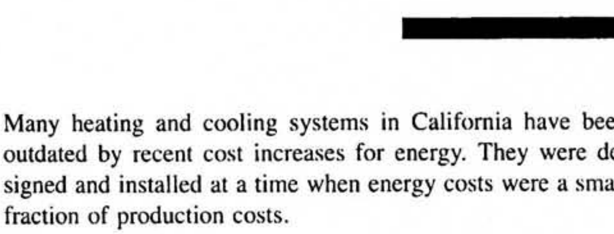
INCREASE EFFICIENCY of HEATING and COOLING SYSTEMS

Many heating and cooling systems in California have been outdated by recent cost increases for energy. They were designed and installed at a time when energy costs were a small fraction of production costs.

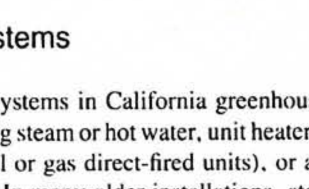
Heating systems

Most heating systems in California greenhouses use a central boiler producing steam or hot water, unit heaters (using steam or hot water or oil or gas direct-fired units), or a combination of these systems. In many older installations, steam or hot water lines, perforated poly tubes, or warm air discharge from unit heaters, will be overhead. Overhead installations do not obstruct the work area of the greenhouse, but increase energy use. The heat distribution system should be lowered near to plant level whenever this will not interfere with greenhouse operations.

LOWER HEAT SOURCE



Under benches—or—near ground level



There are many reasons why heat distribution systems should be located as close to the ground as possible: (1) several recent tests have shown that lowering the heat distribution system is more useful to most plants; (2) less heat is wasted to the upper ridge area of the greenhouse; (3) lowering the heat distribution system is necessary for the installation of thermal blankets or permanent clear poly subroofs; (4) there is increasing experimental evidence that heating the root zone or soil area is beneficial for some crops and permits reduced greenhouse air temperatures, resulting in less energy use for heating; and (5) heating pipes in the top of the greenhouse can transmit as much as one-half of their heat by radiation, and much of this will be lost through the roof.

Infrared heating

(plan for $1.05/ft^2 installed)

There are numerous installations of infrared heaters in California greenhouses. These systems consist of a number of natural gas and propane burners spaced along a connecting steel tube (about 4 inches in diameter). The tube is heated to high temperatures and suspended from the greenhouse roof. Specially designed metal reflectors over the pipes direct heat downward, warming plants and soil directly by radiation. Infrared heating is reported to use less energy because: (1) the burner design provides a higher heat transfer efficiency than most boilers or unit heaters, and (2) air temperature requirements for plants are less, although how much less is unknown.

Growers' reactions are mixed, but generally favorable, depending on the crops grown. Fuel savings of 50 percent, along with better quality plants, have been obtained with infrared heat on geranium cuttings on benches. One rose grower reported savings of 20 percent with infrared heat, but it has not proved beneficial for cucumber production after two seasons of testing.

Infrared systems are still undergoing tests in California, but it appears that this type of heating is best for "short" crops, such as cuttings, transplants, propagation stock, and potted plants such as geraniums and poinsettias. For such crops, infrared heating will probably reduce energy use 35 to 50 percent. Infrared heating should be most effective if the infrared rays can "see" and warm both the leaves and the soil. Where vegetation is thick, or the plants are tall (roses, cucumbers, etc.), some leaves and soil will be shaded from the heat, and the effectiveness of the infrared heat will be reduced.

Costs for such systems vary, but equipment suppliers suggest that costs will average 3½ to 4 cents per square foot of heated area for each degree Fahrenheit of temperature difference between the inside temperature of the greenhouse and the outside design temperature. This suggested cost allowance seems to match the costs for most installations currently in place.

Remember, infrared heating can not be used with thermal curtains unless they are from truss-to-truss and above the infrared heaters.

Soil or bed heating

(plan for 80¢/ft^2 installed)

Soil or bed heating, also referred to as microclimate or root zone heating, has been shown to improve growth and quality of a number of plants and to reduce energy use. Higher root zone temperatures usually allow greenhouse air temperatures to be reduced 5°F from normal or more. Good plant growth and substantial energy savings have been obtained for such plants as poinsettias, cyclamen, calceolaria, primulas, vegetable tranplants and seedlings, many bulb crops, and most foiliage plants. Not all plants have been fully tested with root zone heating.

Bed or root zone heating generally takes the form of heat supplied by 80° to 140°F water that is distributed to the lower parts of plants through tubes embedded in, or on the surface of, soil, sand, concrete, or other materials used as a greenhouse floor or bench surface. Costs for such systems can vary substantially, depending on growers' needs and design requirements, the degree of sophistication and control required, and on the growers' supplies—labor, water heater. One California nursery has 2½ acres of outdoor propagation area with flats on a heated concrete slab. The slab is warmed with 110°F water flowing through embedded copper tubes at a rate of about 2 gallons per minute. Similar indoor propagation areas are used by some growers with formed concrete benches with embedded copper tubes. Total systems like these, including water heaters, cost about $3.45 per square foot of bench or bed area, a rather high cost, but these bed heating systems successfully meet the requirements of these growers. Another grower distributes 120°F water through 1¼-inch polyvinylchloride (PVC) Schedule 40 pipes spaced along the greenhouse floor. Potted plants are placed on the floor between rows of tubes. This is a relatively inexpensive system.

A more recent type of floor heating system uses EPDM (ethylene propylene diene monomer) tubing that will withstand temperatures of 300°F. A Biotherm system uses small diameter EPDM tubes to distribute 90° to 120°F water along the floor or on benches. Flats and pots can be set directly on the tubes. In one California installation, Easter lilies were successfully grown with energy savings of 35 to 50 percent, using reduced night temperatures and 70° to 75°F root zone heating. Pennsylvania State University reported savings of 42 percent (over a conventional glass greenhouse) for poinsettias with this system. Other advantages of this system: it can use small, efficient, point-of-use water heaters, and the greenhouse microclimate can be easily zoned for different plant temperature requirements.

The suggested *plan for* cost of 80 cents per square foot is based on recent quotations for a Biotherm soil or root zone system completely installed, including water heaters. The distribution system itself, without heaters, would be about 40 cents per square foot.

Fuel cost comparisons

In this time of rapidly fluctuating fuel prices, it is useful to compare various available fuel sources for greenhouse heating. The following formula can be used to compare two different fuel sources (A) and (B) for equal heating costs.

$$\text{Cost/unit A} = \text{Cost/unit B} \times \frac{\text{Efficiency A}}{\text{Efficiency B}} \times \frac{\text{Btu/unit A}}{\text{Btu/unit B}}$$

For example: Determine what the cost of No. 5 fuel oil should be to give the same cost of heating as with natural gas.

Fuel A = No. 5 oil at 148,000 Btu/gal and 70% combustion efficiency

Fuel B = Natural gas at 100,000 Btu/therm and 75% combustion efficiency

$$\text{Cost/gal of No. 5 oil} = \text{Cost/therm of NG} \times \frac{70\%}{75\%} \times \frac{148{,}000 \text{ Btu/gal}}{100{,}000 \text{ Btu/therm}} = 1.38 \times \text{Cost/therm of NG}$$

So: if NG = 65.0¢/therm, then No. 5 oil should cost no more than 1.38 × 65.0¢ = 89.8¢/gal.

Any fuels can be compared this way if the present cost of one is known. The last column in table 6 indicates the maximum price for various fuels to be competitive with natural gas at current costs of 65 cents per therm.

TABLE 6. Cost comparison of various energy sources

Fuel	Heat content (Btu/unit)	Combustion efficiency (%)	Maximum unit cost to equal natural gas at 65¢/therm
Natural gas	100,000/therm	75	65.0¢/therm
No. 2 oil	138,000/gal	70	83.7¢/gal
No. 5 oil	148,000/gal	70	89.8¢/gal
No. 6 oil	150,000/gal	70	91.0¢/gal
Propane	90,000/gal	75	58.5¢/gal
Soft coal	22,800,000/ton	60	$118.56/ton
Hard coal	26,000,000/ton	60	$135.20/ton
Electricity	3,413/kwhr	100	3.0¢/kwhr
Oak wood	24,000,000/cord	60	$124.80/cord

Actions to consider

Replace steam traps. In a steam-heated greenhouse (plan for 4 to 6¢/ft^2 of greenhouse floor area), steam traps perform three important functions. They discharge condensate, prevent escape of steam, and discharge air and other incompressible gases on start up. A malfunctioning steam trap can cause excessive energy losses in a steam-heating system. These losses are difficult to prevent without routine inspection. Most growers have a routine maintenance and inspection program, but it might be advisable to periodically install new traps. New traps cost about 4 to 6 cents per square foot of floor area for a typical California greenhouse. This amount, based on the price of new, high-quality traps, does not include installation labor. The labor to install these would probably be less than the cost of one thorough inspection and repair. The possibility for reducing energy losses from the steam distribution system can be substantial.

Decentralize boilers. Most large steam-heated greenhouses have a central boiler. Such systems usually require a long steam distribution line that must be well insulated to reduce heat losses. High pressures are necessary for good steam distribution. Consider using several small boilers distributed around the greenhouse complex when an older central boiler needs to be replaced, or when planning a new greenhouse or heating system. Smaller boilers can be turned off more easily during the day, require lower steam pressures (sometimes eliminating the need for a certified boiler operator), and will allow better control of different environmental needs in various areas of the complex.

Use hot water for heating. There are several reasons why hot water might be more advantageous than steam for greenhouse heating.

1. Hot water is easy to distribute and control.
2. Distribution heat losses are apt to be less with 100° to 150°F water than with high temperature steam.
3. Root zone heating appears to provide better growth with less energy for many crops and is particularly appropriate for most California climates.
4. Low cost plastic pipe can be used for most warm water distribution systems—more pipe will be required than with a steam system, but the total cost should be less.
5. Most steam boilers can be easily converted to hot water boilers, and the present iron steam pipes can also be used.

Hot water systems will allow easy conversion to a solar heated system in the future if they become economical.

Consider alternate fuels. New furnaces are now on the market that will efficiently utilize wood, coal, biomass, and other renewable energy sources. Investigate these when planning new greenhouses or heating systems. These sources of heating might be quite important to us in the future.

Heating system maintenance. All heating systems and their parts require regular maintenance to maintain high efficiency. Regularly inspect and test boilers, inspect unit heaters and their fan belts and louvers, check for leaking steam traps and valves, water valves, boiler water treatment quality, and so forth.

Cooling systems

Most California greenhouses need some form of cooling during certain periods. Methods of cooling require different levels of energy. Subroofs, shading compounds, or natural ventilation use no energy except for initial installation. An automated shading blanket uses minimal energy for pulling, and misting or fogging for cooling use relatively small amounts of electricity for pump operation. Methods that provide a more positive degree of temperature control do require operational energy, often significant amounts. Forced ventilation and pad-and-fan cooling systems both use large quantities of electricity when operating.

In many areas of California, cooling can be sufficient with one or more of the no-energy or low-energy systems. With good planning, energy use for cooling can be minimized. Such planning might also include allowing for periods of high temperature.

Natural ventilation. Some growers in the San Diego area removed all their ventilation fans and redesigned their polyethylene greenhouses with ridge vents that could be closed at night with inflated poly tubes. By opening side curtains they are able to utilize natural ventilation to exchange the air in the greenhouses.

A reasonably safe ventilation system for cooling should have a capacity equal to about one greenhouse volume of air per minute (about 10 cfm/ft^2 of greenhouse floor area). Natural ventilation rarely produces such recommended air change because it depends on wind movement and heated greenhouse air for its power. Nevertheless, most growers who have been in an area for some time should be able to determine if they could operate with a natural ventilation system. Effective natural ventilation generally requires that some greenhouse sides can be opened easily. For winter energy use, however, such easily opened side vents are a disadvantage because they will not be insulated and will often allow unwanted infiltration. One grower installed a double layer polyethylene roll-up curtain that could be inflated when lowered at night, to provide an insulated wall.

Subroofs. The 25% heating energy savings of subroofs is described in Section I. A subroof of clear polyethylene or vinyl will substantially reduce summer cooling, in conjunction with forced ventilation or pad-and-fan cooling. Such a subroof seals off the main greenhouse area from the hot ridge area; it also reduces the cooling volume in the greenhouse so that the ventilation system will move a greater amount of air, proportionately, through the greenhouse. Generally, there is ample sun during hot periods so light reduction due to the subroof is not usually a problem. A 6-mil polyethylene subroof will cost about 15 cents per square foot of greenhouse floor area to install and about 7 cents per square foot to replace. This will reduce energy to operate cooling fans by as much as 20 percent.

Shading compounds. Applying shading compounds to the outside of a greenhouse has been a common practice for years. Shading compounds alone can reduce inside air temperatures 6°F or more by reducing light penetration into the greenhouse. Some horticulturists suggest that applications of shading compounds to a greenhouse cover can often be more harmful than a grower realizes. While it might lower the temperature during periods of bright sun, the light intensity might be reduced unnecessarily on cloudy days.

Shading blankets. The subject of thermal blankets was discussed in Section I. Effective in reducing heating energy, thermal blankets are also useful for hot weather shading. Many current blanket installations consist of two layers of blankets, a solid, opaque layer above a porous material. The porous blankets are available in materials that will allow various amounts of light into the greenhouse. They can be pulled on sunny days to reduce light on the plants, eliminating the need for shading compounds. Reducing light also reduces the heat absorbed by plants, soil, and greenhouse structures that result in the temperature rise of air within the greenhouse. A pulled shading blanket acts as a subroof and increases the efficiency of the cooling system. A blanket installation will cost about $1.00 per square foot of greenhouse floor area.

Misting or fogging. With natural ventilation, misting and fogging uses relatively little energy to evaporatively cool the air in a greenhouse. Mist cooling systems utilize low pressure nozzles. Water droplets from low-pressure mist systems are quite large and do not evaporate quickly, so some free water may wet plants and soil leaching nutrients from both. Free water on plants can spread some diseases and fungi.

Fogging uses very high pressure (around 500 psi) nozzles. High-pressure, low-capacity nozzles (1/2 to 3/4 gallon per hour) are used (about one nozzle for 80 ft^2 of floor area) to produce a very fine atomized fog that fills the greenhouse, cooling the air as it evaporates. Most moisture evaporates before reaching plant level. Fogging can reduce air temperature by 10° to 25°F when used with exhaust fans; and can produce the same level of cooling as a pad-and-fan system, but with reported energy savings of 10 to 25 percent. Fogging is reported to produce more uniform temperatures.

Forced ventilation. Although very energy intensive, forced, or mechanical, ventilation provides positive control of air movement and more temperature control than a natural ventilation system. Forced ventilation systems can be made to operate effectively and automatically with use of thermostats for controlling exhaust fans and mechanized roof or side ventilators.

A forced ventilation system should be controlled so that the minimum number of fans are turned on. Exhaust fan use can be greatly reduced by using polyethylene subroofs or shading blankets to reduce the greenhouse cooling volume.

Exhaust fans for a forced, or mechanical, ventilation system should be able to change at least one greenhouse volume of air per minute. For most greenhouses, this represents an air exchange rate of 8 to 10 cfm per square foot, and should limit the increase in greenhouse air temperature to about 10°F. With this commitment to electrical energy, a grower should maintain the best possible system efficiency to minimize energy costs. The following are some suggestions for doing this:

- For new or replacement motors, choose new style, energy efficient motors. Initial costs will be a little higher, but will be made up by energy savings.
- Control fans with a thermostat that is shaded from the sun and with a small blower that circulates greenhouse air across it. Check correctness of thermostat setting often.
- Exhaust fan outlets should be fitted with shutters that open easily when the fan starts, and prevent air exchange when fans are off.
- Use motorized shutters for air inlets and wire these into the fan control system.
- Check fan and motor bearings often for overheating. Lubricate or replace as necessary.