Solar Greenhouses

Horticulture Resource List

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Abstract

This resource list discusses basic principles of solar greenhouse design, as well as different construction material options. Books, articles and Web sites, and computer software relevant to solar greenhouse design are all provided in a resource list.

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Introduction

All greenhouses collect solar energy. Solar greenhouses are designed not only to collect solar energy during sunny days but also to store heat for use at night or during periods when it is cloudy. They can either stand alone or be attached to houses or barns. A solar greenhouse may be an underground pit, a shed-type structure, or a quonset hut. Large-scale producers use free-standing solar greenhouses, while attached structures are primarily used by home-scale growers.

Passive solar greenhouses are often good choices for small growers, because they are a cost-efficient way for farmers to extend the growing season. In colder climates or in areas with long periods of cloudy weather, solar heating may need to be supplemented with a gas or electric heating system to protect plants against extreme cold. Active solar greenhouses use supplemental energy to move solar heated air or water from storage or collection areas to other regions of the greenhouse. Use of solar electric (photovoltaic) heating systems for greenhouses is not cost-effective unless you are producing high-value crops.

The majority of the books and articles about solar greenhouses were published in the 1970s and 1980s. Since then, much of this material has gone out of print, and some of the publishers are no longer in business. While contact information for companies and organizations listed in these publications is probably out of date, most of the technical information contained in them is still relevant.

Out-of-print publications can often be found in used bookstores, libraries, and through the inter-library loan program. Some publications are also available on the Internet. Bibliofind is an excellent, searchable Web site where many used and out-of-print books can be located.

As you plan to construct or remodel a solar greenhouse, do not limit your research to books and articles that specifically discuss "solar greenhouses." Since all greenhouses collect solar energy and need to moderate temperature fluctuations for optimal plant growth, much of the information on "standard" greenhouse management is just as relevant to solar greenhouses. Likewise, much information on passive solar heating for homes is also pertinent to passive solar heating for greenhouses. As you look through books and articles on general greenhouse design and construction, you will find information relevant to solar greenhouses in chapters or under topic headings that discuss:

- energy conservation
- glazing materials
- floor heating systems
- insulation materials
- ventilation methods

In books or articles on passive solar heating in homes or other buildings, you can find useful information on solar greenhouses by looking for chapters or topic headings that examine:

- solar orientation
- heat absorption materials
- heat exchange through "phase-change" or "latent heat storage materials"

This updated resource list includes listings of books, articles, and Web sites that focus specifically on solar greenhouse as well as on the topics listed above.

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Basic Principles of Solar Greenhouse Design

Solar greenhouses differ from conventional greenhouses in the following four ways. (1) Solar greenhouses:

- have glazing oriented to receive maximum solar heat during the winter.
- use heat storing materials to retain solar heat.
- have large amounts of insulation where there is little or no direct sunlight.
- use glazing material and glazing installation methods that minimize heat loss.
- rely primarily on natural ventilation for summer cooling.

Understanding these basic principles of solar greenhouse design will assist you in designing, constructing, and maintaining an energy efficient structure. You can also use these concepts to help you search for additional information, either on the "Web," within journals, or in books at bookstores and libraries.

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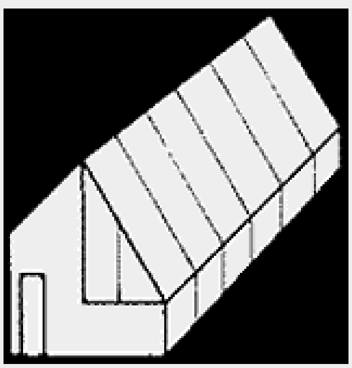
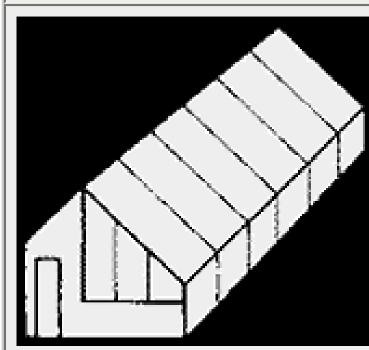
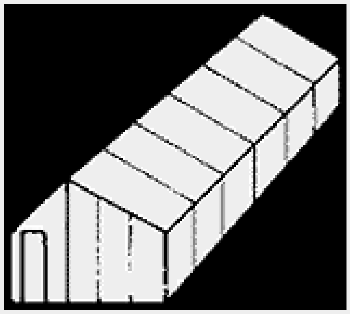
Solar Greenhouse Designs

Attached solar greenhouses are lean-to structures that form a room jutting out from a house or barn. These structures provide space for transplants, herbs, or limited quantities of food plants. These structures typically have a passive solar design.

Freestanding solar greenhouses are large enough for the commercial production of ornamentals, vegetables, or herbs. There are two primary designs for freestanding solar greenhouses: the shed type and the quonset hut. A shed-type solar greenhouse is oriented to have its long axis running from east to west. The south-facing wall is glazed to collect the optimum amount of solar energy, while the north-facing wall is well insulated to prevent heat loss. This orientation is in contrast to that of a conventional greenhouse, which has its roof running north-south to allow for uniform light distribution on all sides of the plants. To reduce the effects of poor light distribution in an east-west oriented greenhouse, the north wall is covered or painted with reflective material. (2)

Freestanding shed-type solar greenhouses (2)	
	For cold winters, northern latitudes and year-round use: • steep north roof pitched tothe highest summer sun angle for maximum year-round light reflection onto plants; • vertical north wall for staching heat storage; • 40-60° sloped south roof glazing; • vertical kneewall high enough to accomodate planting beds and snow sliding off roof; • end walls partially glazed for added light. • The Brace Institute design continues the north roof slope down to the north roof slpe down to the ground (eliminating the north wall), allowing for more planting area in ground, but no heat storage against the north wall.
	For cold winters, middle U.S. latitudes, and year-round use—(similar to the design popularized by Domestic Technology Institute—see resources for plans and address): • 45-60° north roof slope; • vertical north wall for stacking heat storage; • 45° south roof glazing; • vertical kneewall; • part of end walls glazed for additional light.

	For milder winters, southern U.S. latitudes, and year-round use where less heat storage is needed: • 45-70° north roof slope—roof slope steeper and north wall shorter if less space is needed for stacking heat storage; • roof can extend down to ground, eliminating back kneewall if no storage is use; • 20-40° south roof glazing; • front kneewall as high as is needed for access to beds in front; • most of end walls glazed for additional light.

Freestanding quonset greenhouses are rounded, symmetrical structures. Unlike the shed-type solar greenhouses, quonset huts do not have an insulated north side. Solarization of these structures involves practices that enhance the absorption and distribution of the solar heat entering them. This typically involves the collection of solar heat in the soil beneath the floor, in a process called earth thermal storage (ETS), as well as in other storage materials such as water or rocks. Insulation of the greenhouse wall is important for minimizing heat loss. Heat absorption systems and insulation methods are discussed in detail in the following sections.

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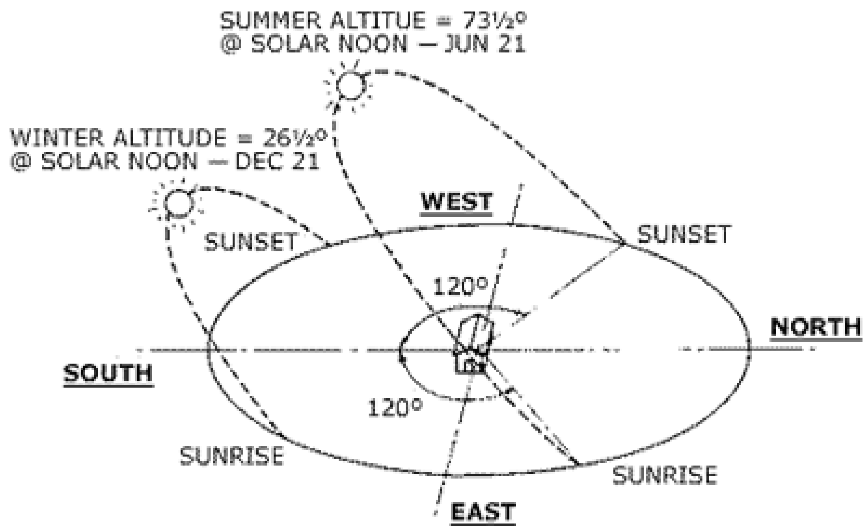
Solar Heat Absorption

The two most critical factors affecting the amount of solar heat a greenhouse is able to absorb are:

- The position or location of the greenhouse in relation to the sun.
- The type of glazing material used.

Solar Orientation

Since the sun's energy is strongest on the southern side of a building, glazing for solar greenhouses should ideally face true south. However, if trees, mountains, or other buildings block the path of the sun when the greenhouse is in a true south orientation, an orientation within 15° to 20° of true south will provide about 90% of the solar capture of a true south orientation. The latitude of your location and the location of potential obstructions may also require that you adjust the orientation of your greenhouse slightly from true south to obtain optimal solar energy gain. (2) Some growers recommend orienting the greenhouse somewhat to the southeast to get the best solar gain in the spring, especially if the greenhouse is used primarily to grow transplants. (3) To determine the proper orientation for solar buildings in your area, visit the sun chart program at the University of Oregon Solar Radiation Monitoring Laboratory Web page. You need to know your latitude, longitude, and time zone to use this program.



Solar path at 40° north latitude (2)

Slope of Glazing Material

In addition to north-south orientation, greenhouse glazing should be properly sloped to absorb the greatest amount of the sun's heat. A good rule of thumb is to add 10° or 15° to the site latitude to get the proper angle. For example, if you are in northern California or central Illinois at latitude 40° north, the glazing should be sloped at a 50° to 55° angle (40° + 10° or 15°). (4)

Glazing

Glazing materials used in solar greenhouses should allow the greatest amount of solar energy to enter into the greenhouse while minimizing energy loss. In addition, good plant growth requires that glazing materials allow a natural spectrum of photosynthetically active radiation (PAR) to enter. Rough-surface glass, double-layer rigid plastic, and fiberglass diffuse light, while clear glass transmits direct light. Although plants grow well with both direct and diffuse light, direct light through glazing subdivided by structural supports causes more shadows and uneven plant growth. Diffuse light passing through glazing evens out the shadows caused by structural supports, resulting in more even plant growth. (5, 6)

Many new greenhouse glazing materials have emerged in recent decades. Plastics now are the dominant type of glazing used in greenhouses, with the weatherability of these materials being enhanced by ultraviolet radiation degradation inhibitors, infrared radiation (IR) absorbency, anti-condensation drip surfaces, and unique radiation transmission properties. (7)

The method used for mounting the glazing material affects the amount of heat loss. (8) For example, cracks or holes caused by the mounting will allow heat to escape, while differences in the width of the air space between the two glazes will affect heat retention. Installation and framing for some glazing materials, such as acrylics, need to account for their expansion and contraction with hot and cold weather. (7) As a general rule, a solar greenhouse should have approximately 0.75 to 1.5 square feet of glazing for each square foot of floor space. (1)

Table 1. Glazing Characteristics

Glass—single layer Light transmission*: 85-90% R-value**: 0.9 Advantages: • Lifespan indefinite if not broken • Tempered glass is stronger and requires fewer support bars Disadvantages: • Fragile, easily broken • May not withstand weight of snow • Requires numerous supports • Clear glass does not diffuse light	**Factory sealed double glass** Light transmission*: 70-75% R-value**: double layer 1.5–2.0, low-e 2.5 Advantages: • Lifespan indefinite if not broken • Can be used in areas with freezing temperatures Disadvantages: • Heavy • Clear glass does not diffuse light • Difficult to install, requires precise framing
Polyethylene—single layer Light transmission*: 80-90% - new material R-value**: single film 0.87 Advantages: • Heat loss significantly reduced when a blower is used to provide an air space between the two layers • IR films have treatment to reduce heat loss • No-drop films are treated to resist condensation • Treatment with ethyl vinyl acetate results in resistance to cracking in the cold and tearing • Easy to install, precise framing not required • Lowest cost glazing material Disadvantages: • Easily torn • Cannot see through • UV-resistant polyethylene lasts only 1–2 years • Light transmission decreases over time • Expand and sag in warm weather, then shrink in cold weather	**Polyethylene—double layer** Light transmission*: 60-80% R-value** double films: 5ml film 1.5, 6ml film 1.7 Advantages: • Heat loss significantly reduced when a blower is used to provide an air space between the two layers • IR films have treatment to reduce heat loss • No-drop films are treated to resist condensation • Treatment with ethyl vinyl acetate results in resistance to cracking in the cold to tearing • Easy to install, precise framing not required • Lowest cost glazing material Disadvantages: • Easily torn • Cannot see through • UV-resistant polyethylene lasts only 1–2 years • Light transmission decreases over time • Expand and sag in warm weather, then shrink in cold weather
Polyethylene—corrugated high density Light transmission*: 70-75% R-value**: 2.5-3.0 Advantages: • Mildew, chemical, and water resistant • Does not yellow Disadvantages: n/a	**Laminated Acrylic/Polyester film—double layer** Light transmission*: 87% R-value**: 180% Advantages: • Combines weatherability of acrylic with high service temperature of polyester • Can last 10 years or more Disadvantages: • Arcrylic glazings expand and contract considerably; framing needs to allow for this change in size • Not fire resistant
Impact modified acrylic—double layer Light transmission*: 85% Advantages: • Not degraded or discolored by UV light • High impact strength, good for locations with hail Disadvantages: • Arcrylic glazings expand and contract considerably; framing needs to allow for this change in size • Not fire resistant	**Fiber reinforced plastic (FRP)** Light transmission*: 85-90% - new material R-value**: single layer 0.83 Advantages: • The translucent nature of this material diffuses and distributes light evenly • Tedlar treated panels are resistant to weather, sunlight, and acids • Can last 5 to 20 years Disadvantages: • Light transmission decreases over time • Poor weather resistance • Most flammable of the rigid glazing materials • Insulation ability does not cause snow to melt

Polycarbonate—double wall rigid plastic Light transmission*: 83% R-value**: 6mm 1.6, 8mm 1.7 Advantages: • Most fire resistant of plastic glazing materials • UV resistant • Very strong • Lightweight • Easy to cut and install • Provides good performance for 7-10 years Disadvantages: • Can be expensive • Not clear, translucent	**Polycarbonate film—triple and quad wall rigid plastic** Light transmission*: 75% R-value** triple walls: 8mm 2.0–2.1, 16mm 2.5 R-value** quad wall: 6mm 1.8, 8 mm 2.1 Advantages: • Most fire resistant of plastic glazing materials • UV resistant • Very strong • Lightweight • Easy to cut and install • Provides good performance for 7-10 years Disadvantages: • Can be expensive • Not clear, translucent
Sources: (2, 6, 7, 13, 14) * note that framing decreases the amount of light that can pass through and is available as solar energy ** R-Value is a common measure of insulation (hr°Fsq.ft/BTU)	

You need to understand four numbers when selecting glazing for solar greenhouses. Two numbers describe the heat efficiency of the glazing, and the other two numbers other numbers are important for productive plant growth. Many glazing materials include a National Fenestration Rating Council sticker that lists the following factors:

• *The SHGC or solar heat gain coefficient* is a measure of the amount of sunlight that passes through a glazing material. A number of 0.60 or higher is desired.

• *The U-factor* is a measure of heat that is lost to the outside through a glazing material. A number of 0.35 BTU/hr-ft2-F or less is desired.

• *VT or visible transmittance* refers to the amount of visible light that enters through a glazing material. A number of 0.70 or greater is desired.

• *PAR or photosynthetically active radiation* is the amount of sunlight in the wavelengths critical for photosynthesis and healthy plant growth. PAR wavelength range is 400-700 nanometers (a measure of wavelength).

Note: When choosing glazing, look at the total visual transmittance, not PAR transmittance, to see whether the material allows the spectrum of light necessary for healthy plant growth.

In addition to energy efficiency and light transmission, you should consider the following when choosing glazing materials for your greenhouse:

• Lifespan
• Resistance to damage from hail and rocks
• Ability to support snowload
• Resistance to condensation
• Sheet size and distance required between supports
• Fire resistance
• Ease of installation

(Based on 6, 9, 10, 11, 12, 13, 14)

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Solar Heat Storage

For solar greenhouses to remain warm during cool nights or on cloudy days, solar heat that enters on sunny days must be stored within the greenhouse for later use. The most common method for storing solar energy is to place rocks, concrete, or water in direct line with the sunlight to absorb its heat. (1)

Brick or concrete-filled cinder block walls at the back (north side) of the greenhouse can also provide heat storage. However, only the outer four inches of thickness of this storage material effectively absorbs heat. Medium to dark-colored ceramic tile flooring can also provide some heat storage. (15) Walls not used for heat absorption should be light colored or reflective to direct heat and light back into the greenhouse and to provide a more even distribution of light for the plants.

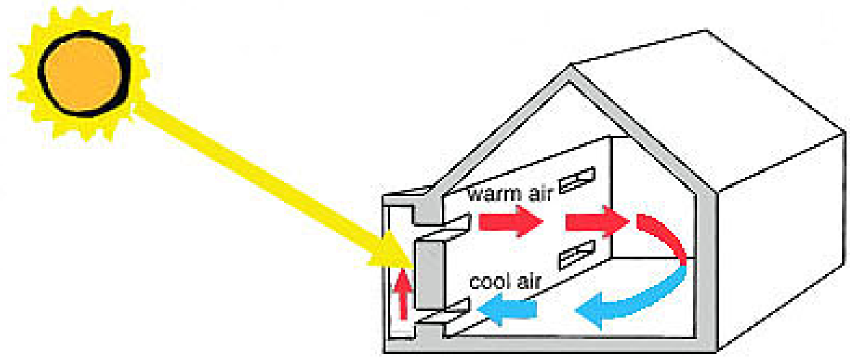
Storage Materials

The amount of heat storage material required depends on your location. If you live in southern or mid-latitude locations, you will need at least 2 gallons of water or 80 pounds of rocks to store the heat transmitted through each square foot of glazing. (16) If you live in the northern states, you will need 5 gallons or more of water to absorb the heat that enters through each square foot of glazing. (1) Approximately three square feet of four-inch thick brick or cinder block wall is required for each square foot of south-facing glass. (15)

The amount of heat storage material required also depends on whether you intend to use your solar greenhouse for extending the growing season, or whether you want to grow plants in it year-round. For season extension in cold climates, you will need 2 ½ gallons of water per square foot of glazing, or about half of what you would need for year-round production. (2)

If you use water as heat storage material, ordinary 55-gallon drums painted a dark, non-reflective color work well. Smaller-sized containers, such as milk jugs or glass bottles are more effective than 55-gallon drums in providing heat storage in areas with frequent cloud. The smaller-size container has a higher ratio of surface area, resulting in more rapid absorption of heat when the sun does shine. (14) Unfortunately, plastic containers degrade after two or three years in direct sunlight. Clear glass containers provide the advantages of capturing heat better than dark metal containers and not degrading, but they can be easily broken. (17)

Trombe walls are an innovative method for heat absorption and storage. These are low walls placed inside the greenhouse near the south-facing windows. They absorb heat on the front (south-facing) side of the wall and then radiate this heat into the greenhouse through the back (north-facing) side of the wall. A Trombe wall consists of an 8- to 16-inch thick masonry wall coated with a dark, heat-absorbing material and faced with a single or double layer of glass placed from 3/4" to 6" away from the masonry wall to create a small airspace. Solar heat passes through the glass and is absorbed by the dark surface. This heat is stored in the wall, where it is conducted slowly inward through the masonry. If you apply a sheet of metal foil or other reflective surface to the outer face of the wall, you can increase solar heat absorption by 30-60% (depending on your climate) while decreasing the potential for heat loss through outward radiation. (10, 18)



Trombe wall.
Photo courtesty: Australian Center for Renewable Energy

"Water walls" are a variation of the Trombe wall. Instead of a masonary wall, water-filled containers are placed in line with the sun's rays between the glazing and the greenhouse working space. The water can be in hard plastic tubes or other sturdy containers, and the top of the wall can serve as a bench. The *Solviva* solar greenhouse "water wall" consists of two 2x4 stud walls, with the studs placed two feet on centers. A one-foot spacer connects the two walls. Plastic-covered horse fence wire was then fastened to each stud wall, and heavy duty, dark-colored plastic water bags were inserted into the space between the two walls. The stud walls were positioned vertically in line with the sun's rays prior to the bags being filled with water. (19) Both the Solviva and Three Sisters Farm Web pages provide designs for constructing solar greenhouses using water walls.

You can use rocks instead of water for heat storage. The rocks should be ½ to 1½ inches in diameter to provide high surface area for heat absorption. (5) They can be piled in wire-mesh cages to keep them contained. Since rocks have a much lower BTU storage value than water (35 BTU/sq.ft/°F for rocks versus 63 for water) (13), you will need three times the volume of rocks to provide the same amount of heat storage. Rocks also have more resistance to air flow than water, resulting in less efficient heat transfer. (20)

Whichever material you choose to use for heat storage, it should be placed where it will collect and absorb the most heat, while losing the least heat to the surrounding air. Do not place the thermal mass so that it touches any exterior walls or glazing since this will quickly draw the heat away.

Phase-change

Instead of water or rocks for heat storage, you can use "phase change materials." While phase change materials are usually more expensive than conventional materials, they are 5 to 14 times better able to store heat than water or rocks. Thus, they are useful when space is limited. Phase change materials include

1. disodium phosphate dodecahydrate,
2. sodium thiosulfate pentahydrate,
3. paraffin,
4. Glauber's salt (sodium sulphate dcahydrate),
5. calcium chloride hexahydrate, and
6. fatty acids. (21, 22)

They absorb and store heat when they change from solid to liquid phase, then they release this heat when they change back into a solid phase. (5) Calcium chloride hexahydrate has a heat storing capacity 10 times that of water. (23) These materials are usually contained in sealed tubes, with several tubes being required to provide sufficient heat storage. Because of the ability of phase change materials to absorb high quantities of heat, they are also useful in moderating greenhouse temperatures in the summer.

Most of the research on the use of phase-change materials for greenhouses has been conducted in Europe, Israel, Japan, and Australia. In Israel, phase-change materials were incorporated into greenhouse glazing, which increased heat capture and retention, but reduced the transparency of the glazing on cloudy days when the phase change material did not become liquid. (24) I was able to identify two companies—one in the U.S. and another in Australia—that sell underfloor heating systems using phase change materials. (25, 26) Phase-change drywall, currently under research, incorporates phase-change materials inside common wallboard to increase its heat storage capacity and could replace heavier, more expensive, conventional thermal masses used in passive solar space heating. (27) See the reference section for a listing of publications and Web sites that provide additional information about phase change materials.

For more information, see the Energy Efficiency and Renewable Energy fact sheet entitled "Thermal Energy Storage Concrete & Phase Change TES." The Phase Change Thermal Energy Storage Web site provides a detailed discussion of this technology.

For many homeowners, building an attached solar greenhouse is very appealing. They believe that they can extend their garden's growing season while reducing their home heating bills. Unfortunately, there is a contradiction between the use of a greenhouse to grow plants and the use of it as a solar collector for heating the house. (9, 28)

• To provide heat for a home, a solar collector needs to be able to collect heat in excess of what plants can tolerate.

• Much of the heat that enters into a greenhouse is used for evaporating water from the soil and from plant leaves, resulting in little storage of heat for home use.

• A home heat collector should be sealed to minimize the amount of heat loss. Greenhouses, however, require some ventilation to maintain adequate levels of carbon dioxide for plant respiration and to prevent moisture build-up that favors plant diseases.

Bioshelters provide an exception to this rule. In bioshelters, the food-producing greenhouse is not an "add-on" to the house but is an integral part of the living space. Bioshelters often integrate fish or small animals with vegetable production to complete nutrient cycles. Biological control measures and plant diversity are used to manage pests in a way that is safe for people and pets in the living quarters. First pioneered by The New Alchemy Institute of East Falmouth, Massachusetts, in the 1970s, Solviva and the Three Sisters Farm carry on the bioshelter tradition.

Active Solar

An active method for solar heating greenhouses uses "subterranean heating" or "earth thermal storage solar heating." This method involves forcing solar heated air, water, or phase change materials through pipes buried in the floor. If you use hot air for subsurface heating, inexpensive flexible drainage or sewage piping about 10 centimeters (4 inches) in diameter can be used for the piping. Although more expensive, corrugated drainage tubing provides more effective heating than smooth tubing, since it allows for greater interaction between the heat in the tube and the ground. The surface area of the piping should be equal to the surface area of the floor of the greenhouse. You can roughly calculate the number of feet of four-inch tubing you will need by dividing the square feet of greenhouse floor area by two. Once installed, these pipes should be covered with a porous flooring material that allows for water to enter into the soil around them, since moist soil conducts heat more effectively than dry soil. The system works by drawing hot air collected in the peak of the roof down through pipes and into the buried tubing. The hot air in the tubes warms the soil during the day. At night, cool air from the greenhouse is pumped through the same tubing, causing the warm soil to heat this air, which then heats the greenhouse. (29, 30) For more information on this design, see *Solar Greenhouses for Commercial Growers* (29), or visit the Web page of Going Concerns Unlimited, a solar energy company in Colorado.

Root-zone thermal heating with water is normally used in conjunction with gas-fired water heaters. This system can be readily adapted to solar and works well with both floor and bench heat. Bench-top heating with root-zone thermal tubing is widely practiced in modern greenhouse production and can be installed easily. A permanent floor heating system consists of a series of parallel PVC pipes embedded on 12" to 16" centers in porous concrete, gravel, or sand. Water is heated in an external solar water heater then pumped into the greenhouse and circulated through the pipes, warming the greenhouse floor. Containerized plants sitting directly on the greenhouse floor receive root-zone heat. Additional information on root zone heating can be found in the ATTRA publication *Root Zone Heating for Greenhouse Crops*.

The *Solviva* greenhouse uses a variation of active solar heating. The system in this greenhouse relies on heat absorption by a coil of black polybutylene pipe set inside the peak of the greenhouse. The pipe coil lays on a black background and is exposed to the sun through the glazing. A pump moves water from a water tank, located on the floor of the greenhouse, to the coiled pipe and back to the tank. Water heated within the coils is capable of heating the water in the tank from 55°F to 100°F on a sunny day. The heat contained in the water tank helps keep the greenhouse warm at night. (19)

Greenhouse management practices also can affect heat storage. For example, a full greenhouse stores heat better than an empty one. However, almost half of the solar energy is used to evaporate water from leaf and soil surfaces and cannot be stored for future use. (5, 31) Solar heat can be complemented with heat from compost as described in the ATTRA publication *Compost Heated Greenhouses*. Besides adding some heat to the greenhouse, increased carbon dioxide in the greenhouse atmosphere, coming from the decomposition activities of the microorganisms in the compost, can increase the efficiency of plant production.

While solar greenhouses can extend your growing season by providing relatively warm conditions, you should carefully select the types of plants that you intend to grow, unless you are willing to provide backup heating and lighting.

Vegetables and herbs that are suitable for production in a winter solar greenhouse include:

Cool temperature tolerant: Basil, celery, dill, fennel, kale, leaf lettuce, marjoram, mustard greens, oregano, parsley, spinach, Swiss chard, turnips, cabbage, collards, garlic, green onions, and leeks.

Require warmer temperatures: Cherry tomatoes, large tomatoes, cucumbers (European type), broccoli, edible pod peas, eggplant, and peppers.

(Based on 28)

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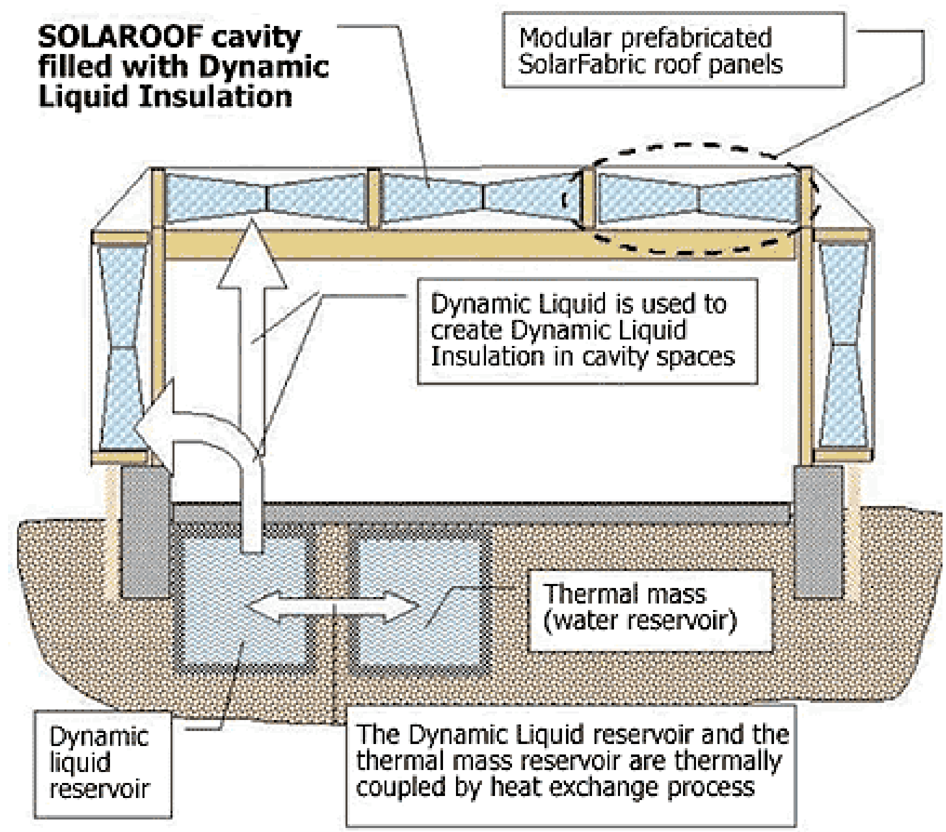
Insulation

Wall and Floor Insulation

Good insulation helps to retain the solar energy absorbed by thermal mass materials. Keeping heat in requires you to insulate all areas of the greenhouse that are not glazed or used for heat absorption. Seal doors and vents with weather stripping. Install glazing snugly within casements. Polyurethane foams, polystyrene foams, and fiberglass batts are all good insulating materials. But these materials need to be kept dry to function effectively. A vapor barrier of heavy-duty polyethylene film placed between the greenhouse walls and the insulation will keep your greenhouse well insulated. (1) Unglazed areas should be insulated to specifications of your region. For example, insulation R-value R-19 is specified for greenhouses in Illinois (1) and in Missouri (24), while R-21 is recommended for walls in New Mexico. (10) The ZIP-Code Insulation Program Web site provides a free calculator for finding recommended insulation R-values for houses based on your zip code.

Richard Nelson of the Solaroofgarden organization developed an innovative way to insulate greenhouse walls in a quonset hut style greenhouse. This system involves constructing a greenhouse with a double layer of plastic sheeting as glazing. Bubble machines (such as are used to create bubbles at parties) are installed in the peak of the greenhouse between the two layers of plastic. At least two generators should be installed, at either end of the greenhouse. During the winter, the bubble machines face north and blow bubbles into space between two sheets of plastic on the north side of the greenhouse to provide R-20 or higher insulation for northern winters. During the summer, the bubble machines can be turned to face south to provide shading against high heat. (33)

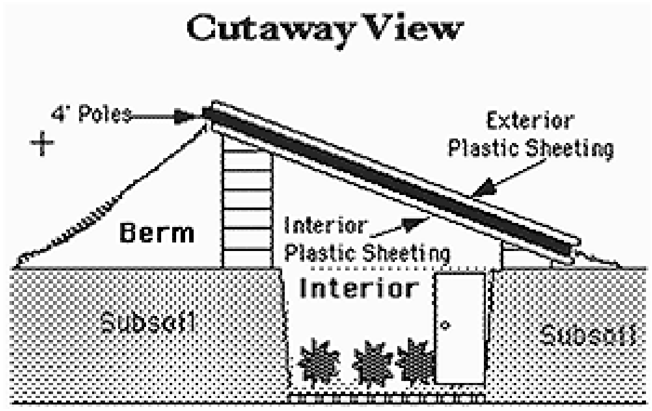


Bubble greenhouse design.

On greenhouse floors, brick, masonry, or flagstone serves as a good heat sink. However, they can quickly lose heat to the ground if there is not an insulating barrier between the flooring and the soil. To protect against heat loss, insulate footings and the foundation with 1- to 2-inch sheets of rigid insulation or with a 4-inch-wide trench filled with pumice stone that extends to the bottom of the footings. You can also insulate flooring with four inches of pumice rock. Besides insulating the floor, it also allows water to drain through. (16)

External Insulation

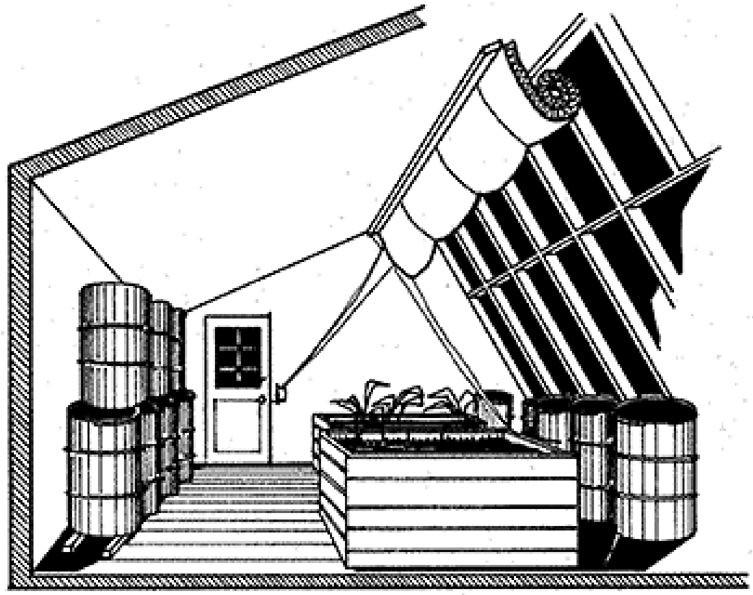
You can also insulate your greenhouse by burying part of the base in the ground or building it into the side of a south-facing hill. (5) Straw bales or similar insulating material can also be placed along the unglazed outside walls to reduce heat loss from the greenhouse. (34) Underground or bermed greenhouses provide excellent insulation against both cold winter weather and the heat of summer. They also provide good protection against windy conditions. (35) Potential problems with an underground greenhouse are wet conditions from the water table seeping through the soil on the floor and the entry of surface water through gaps in the walls at the ground level. To minimize the risk of water rising through the floor, build the underground greenhouse in an area where the bottom is at least five feet above the water table. To prevent water from entering the greenhouse from the outside, dig drainage ditches around the greenhouse to direct water away from the walls. Also, seal the walls with waterproof material such as plastic or a fine clay. An excellent description of how to build a simple pit greenhouse is provided at the Web page for the Benson Institute, a division of the College of Biology and Agriculture at Brigham Young University (BYU). This Institute has a campus in Bolivia where students built an underground greenhouse based on local, traditional practices. (36)



The Walipini greenhouse, a traditional underground greenhouse from Bolivia. (36)

Glazing is what allows light and heat into a solar greenhouse. It can also be the greatest area for heat loss. As mentioned previously, increasing the insulating value of glazing often decreases the amount of sunlight entering the greenhouse. When selecting glazing for your greenhouse, look for materials that provide both good light transmission and insulating value. For example, polyethylene films referred to as "IR films" or "thermal films" have an additive that helps reduce heat loss. (37) Double or triple glazing provides better insulation than single glazing. Some greenhouse growers apply an extra layer of glazing—usually a type of film—to the interior of their greenhouses in winter to provide an extra degree of insulation. Adding a single or double layer of polyethylene film over a glass house can reduce heat loss by as much as 50%. (38) By using two layers of polyethylene film in plastic-film greenhouses with a small fan blowing air between them to provide an insulating air layer, heat losses can be reduced by 40% or more, as compared to a single layer of plastic. (39)

Greenhouse curtains limit the amount of heat lost through greenhouse glazing during the night and on cloudy days. By installing greenhouse insulation sheets made from two-inch thick batts of polystyrene, you can reduce by almost 90% the heat that would otherwise be lost through the glazing. For a small greenhouse where labor is not a large constraint, you can manually install the polystyrene sheets at night and remove them in the morning. Magnetic clips or Velcro fasteners will facilitate the installation. (1) Alternatively, you can install thermal blankets made of polyethylene film, foam-backed fiberglass, or foil-faced polyethylene bubble material. These blankets are supported on wire tracks and can be raised or lowered using pulleys. While greenhouse curtains composed of thermal blankets are usually opened and shut manually, a few manufactures have motorized roll-up systems that store the blanket near the greenhouse peak. (5)



Solar greenhouse with solar curtains, water wall, and water heat storage on the north wall. (2)

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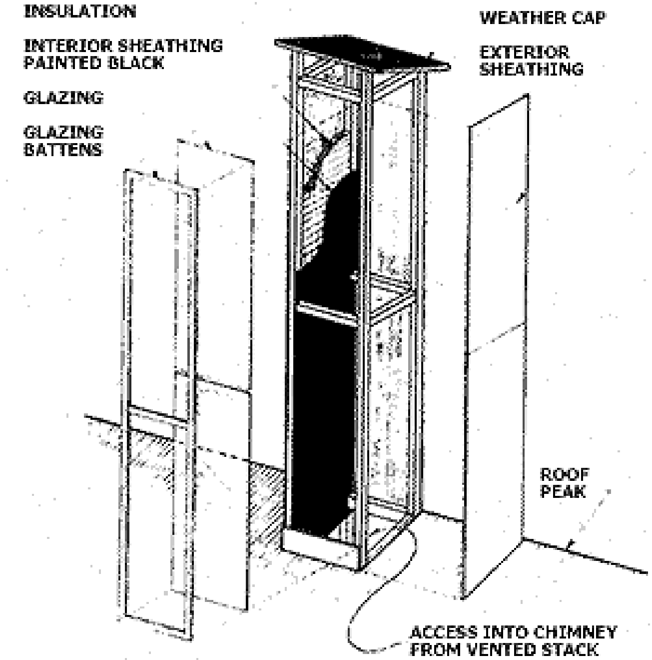
Ventilation

A building designed to collect heat when temperatures are cold also needs to be able to vent heat when temperatures are warm. Air exchange is also critical in providing plants with adequate levels of carbon dioxide and controlling humidity. Because of the concentrated air use by plants, greenhouses require approximately two air exchanges per minute (in contrast to the one-half air exchange per minute recommended for homes). To determine the flow requirements for your greenhouse, multiply the volume of the greenhouse by two to get cubic feet of air exchange per minute, which is the rate used in determining the capacity of commercial evaporative coolers.

Roof ridge and sidewall vents provide natural ventilation. The sidewall vents allow cool air to flow into the sides of the greenhouse, while ridge vents allow the rising hot air to escape. Some wind is necessary for this type of ventilation system to function effectively. On still, windless days, fans are necessary to move air through the greenhouse. The area of the venting should be equal to between 1/5 to 1/6 of the greenhouse floor area. (1)

Solar chimneys are passive solar collectors attached to the highest point on the greenhouse and are combined with vents or openings on either end of the greenhouse. The chimney has an inlet that draws warm air from inside the greenhouse and an outlet that discharges it to the outdoors. To enhance solar gain inside the chimney and increase airflow, the inner surface of the chimney stack is glazed or painted black. A ventilator turbine added to the top of the chimney provides an additional force to pull warm air up from inside the greenhouse. (40)

Thermal storage materials are effective in



A solar chimney. (2)

keeping a greenhouse cool in summer as well as keeping it warm in winter. Since these materials absorb heat during the day, less heat radiates within the greenhouse when the sun is shining. When the sun goes down, heat released from the thermal storage materials can be vented out of the greenhouse. (2)

Removing external shading can also decrease heat build-up within the greenhouse. Shading provided by mature trees is not recommended. Older books on solar greenhouse design (e.g. 2) argue that deciduous trees can provide shade in the summer, but allow for plenty of sunlight to enter through the glazing in the winter after the leaves are gone. However, more recent literature notes that a mature, well-formed deciduous tree will screen more than 40% of the winter sunlight passing through its branches, even when it has no leaves. (31)

Active solar cooling systems include solar air conditioning units and photovoltaics set up to run standard evaporative cooling pads. Both are more complex and expensive to equip than passive systems.

Putting It All Together

Designing and building a solar greenhouse can be an exciting and rewarding project. Feel free to rely on the older literature to provide you with basic siting, design, and construction guidelines. However, incorporating new glazing, heat storage, and insulating materials into your design can greatly enhance the efficiency of your structure. Several consulting companies can provide you with blueprints and design assistance, often at a reasonable cost. See the **Resources** list for names and contact information for these companies. Of course, you need to weigh the costs of these new technologies against the value of your greenhouse-grown crops. As you become familiar with the principals of passive solar design, you may want to experiment with ways of harnessing the power of the sun within your greenhouse to produce better plants throughout the year.

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12. BTS. 2001. Passive Solar Design. Technology Fact Sheet. U.S. Department of Energy. Office of Building Technolgy, State and Community Programs. Accessed at: www.nrel.gov/docs/fy01osti/29236.pdf (PDF / 232 K)

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Resources

Books

- Solar Greenhouses
- Energy Conservation in Greenhouses
- Passive Solar Home Design

Note: Many of the books listed below are out of print. You may be able to locate these books at a public library or in a good used bookstore. Bibliofind is an excellent, searchable Web site where many used and out-of-print books can be located.

Solar Greenhouses

Alward, Ron, and Andy Shapiro. 1981. Low-Cost Passive Solar Greenhouses. National Center for Appropriate Technology, Butte, MT. 173 p.

> Provides a good introduction to lean-to and small solar greenhouses. Available free from ATTRA: 1-800-346-9140 (hard copy only, while supplies last).

Anon. 1980. A Solar Adapted Greenhouse Manual and Design. Miller-Solsearch, Charlottetown, PEI, Canada.

Anon. 1979. Manual for Maritime Solar Heated Greenhouses. Overview, Wolfville, Nova Scotia. 71 p.

Babcock, Joan, et al. 1981. A Place in the Sun: A Guide to Building an Affordable Solar Greenhouse. R.J.K. Solar, Gillette, NJ. 28 p.

Craft, Mark A. (Editor). 1983. Winter Greens: Solar Greenhouses for Cold Climates. Firefly Books. Scarborough, Ont. 262 p. (Out of Print).

Clegg, Peter. 1978. The Complete Greenhouse Book: Building and Using Greenhouses from Cold-Frames to Solar Structures. Storey Books. Pownal, VT. 280 p. (Out of print).

Conserver Society Products Cooperative. 1979. Solar Greenhouse Workbook. Conserver Society Cooperative, Ottawa, Canada. 43 p.

DeKorne, James B. 1992. The Hydroponic Hot House: Low-Cost, High Yield Greenhouse Gardening. Breakout Productions, Incorporated 178 p.

> An illustrated guide to alternative-energy greenhouse gardening. It includes directions for building several different greenhouses.

Edey, Anna. 1998. Solviva: How to Grow $500,000 on One Acre and Peace on Earth. Trailblazer Press, Vineyard Haven, MA. 225 p.

> One of few recent books written on solar greenhouses. Available for $35 from:
>
> Solviva
> RFD 1 Box 582
> Vineyard Haven, MA 02568
> 508-693-3341
> 508-693-2228 FAX
> solviva@vineyard.net

Ellwood, Charles C. How to Build and Operate Your Greenhouse: Growing Methods, Hydroponics, Nutrient Formulas, Plans, Costs, Heating and Cooling, Introduction to Solar heating. H.P. Books. Tucson, AZ. 144 p. (Out of print).

Freeman, Mark. 1997. Building Your Own Greenhouse. Stackpole Books, Mechanicsburg, PA. 208 p.

> A guide to designing and constructing cold frames, free-standing greenhouses, and attached to the house solar greenhouses. Available for $18.95 from:
>
> Stackpole Books
> 5067 Ritter Rd.
> Mechanicsburg, PA 17055
> 800-732-3669

Fontanetta, John. 1979. Passive Solar Dome Greenhouse Book. Storey Books. Pownal, VT. (Out of print).

Fuller, R.J. 1992. Solar Greenhouses for the Home Gardener. Victorian Dept. of Food and Agriculture, Melbourne, Australia. 27 p.

Geery, Daniel. 1982. Solar Greenhouses: Underground. TAB Books, Blue Ridge Summit, PA. 400 p.

> Focuses on earth-sheltered solar greenhouse structures. Good information on design, function, construction, and operation of greenhouses. Many useful tables and charts. (Out of print).

Hayes, John (ed.). 1979. Proceedings from the Conference on Energy-Conserving, Solar-Heated Greenhouses. Held in Plymouth, MA, April, 1979. New England Solar Energy Association, Brattleboro, VT. 328 p.

Head, William. 1984. Fish Farming in Your Solar Greenhouse. Amity Foundation, Eugene, OR. 50 p. (Out of print).

Magee, Tim. 1979. A Solar Greenhouse Guide for the Pacific Northwest. Ecotope, Seattle, WA. 91 p.

Available for $6 from:
Ecotope
2812 E. Madison
Seattle, WA 98112
206-322-3753

Mazria, Edward. 1979. The Passive Solar Energy Book. Rodale Press, Emmaus, PA. 435 p. (Out of print, but usually available from used book sellers).

McCullagh, James C. (ed.) 1978. The Solar Greenhouse Book. Rodale Press, Emmaus, PA. 328 p.

Comprehensive overview of small attached, pit, and free-standing solar greenhouses. Out of print, but usually available from used booksellers.

Monk, G.J., D.H. Thomas, J.M. Molnar, and L.M. Staley. 1987. Solar Greenhouses for Commercial Growers. Publication 1816. Agriculture Canada, Ottawa, Canada. 48 p.

Nearing, Helen, and Scott Nearing. 1977. Building and Using Our Sun-Heated Greenhouse: Grow Vegetables All Year-Round. Storey Books, Pownal, VT. 148 p. (Out of print).

Shapiro, Andrew. 1985. The Homeowner's Complete Handbook for Add-On Solar Greenhouses and Sunspaces. Rodale Press, Emmaus, PA. 355 p.

Updates and expands on material in The Solar Greenhouse Book (see above). (Out of print).

Smith, Shane. 1982. The Bountiful Solar Greenhouse. John Muir Publications. Santa Fe, NM. 221 p. (Out of print).

Stone, Greg. 1997. Building a Solar-Heated Pit Greenhouse. Storey Communications, Pownal, VT. 32 p. (Out of print).

Strickler, Darryl J. 1983. Solarspaces : How (and Why) to Add a Greenhouse, Sunspace, or Solarium to Your Home. Van Nostrand Reinhold Co., New York, NY. 154 p. (Out of print).

Taylor, Ted M. 1999. Secrets to a Successful Greenhouse and Business : A Complete Guide to Starting and Operating A High-Profit Organic or Hydroponic Business That Benefits the Environment. GreenEarth Publishing, Melbourne, FL. 280 p.

Includes solar greenhouse design plans as well as greenhouse operation and business development information. Ordering information available at: www.greenhouse.net

Thomas, Stephen G., John R. McBride, James E. Masker, and Keith Kemble. 1984. Solar Greenhouses and Sunspaces: Lessons Learned. National Center for Appropriate Technology. Butte, MT. 36 p. (Out of print).

Williams, T. Jeff, Susan Lang, and Larry Hodgson. 1991. Greenhouses: Planning, Installing and Using Greenhouses. Ortho Books, San Ramon, CA. 112 p.

Yanda, William F. 1976. An Attached Solar Greenhouse. Lightning Tree Press, Boulder, CO. 18 p. (Out of print).

Yanda, William F., and Rick Fisher. 1980. The Food and Heat Producing Solar Greenhouse: Design, Construction, and Operation. John Muir Publishing, Santa Fe, NM. 208 p.
(Out of print).

Energy Conservation in Greenhouses

Aldrich, Robert A., and John W. Bartok, Jr. 1989. Greenhouse Engineering. NRAES-33. Cornell University, Ithaca, NY. 203 p.

> Provides a comprehensive treatment of the design and construction of medium- to large-scale greenhouses, with over 60 tables and 100 diagrams. $30.

Bartok, Jr., John W. 2001. Energy Conservation for Commercial Greenhouses. NRAES-3. Cornell University, Ithaca, NY. 84 p.

> Reviews the merits and limitations of current energy-conservation strategies for commercial greenhouses. Topics covered include principles of heat loss, site selection and modification, construction materials, insulation, fuels and heating, ventilation and cooling, space utilization, utilities, strategies for reducing trucking costs, and managing for efficiency.

Bartok, Jr., John W. 2000. Greenhouses for Homeowners and Gardeners. NRAES-137. Cornell University, Ithaca, NY. 214 p.

> Covers every aspect of designing and constructing a home greenhouse. Eight chapters discuss the following topics: greenhouse basics, selecting a greenhouse, greenhouse planning, framing materials and glazing, greenhouse layouts and equipment, the greenhouse environment, window greenhouses and growth chambers, and garden structures.

The three books listed above are available from:

> Natural Resource, Agriculture, and Engineering Service (NREAS)
> 152 Riley-Robb Hall
> Ithaca, NY 14853-5701
> 607-255-7654
> 607-254-8770 FAX
> NRAES@cornell.edu

Bond, T.E., J.F. Thompson, and Ray F. Hasek. 1985. Reducing Energy Costs in California Greenhouses. Leaflet 21411. Cooperative Extension University of California. 24 p.

Passive Solar Home Design

Anderson, Bruce, and Malcolm Wells. 1981. Passive Solar Energy: The Home-owner's Guide to Natural Heating and Cooling. Brick House Pub. Co. 197 p.

Crosbie, Michael J. (ed.) 1998. The Passive Solar Design and Construction Handbook. John Wiley and Sons Ltd., New York. 291 p.

Creech, Dennis B. 1988. Homeowner's Guide to Energy Efficient and Passive Solar Homes. DIANE Publishing Co.

Kachadorian, James. 1997. The Passive Solar House: Using Solar Design to Heat and Cool Your Home. Chelsea Green Publishing Co. White River Junction, VT $25.
Available from The Solar Energy Organization Web page.

Levy, M. Emanuel, Deane Evans, and Cynthia Gardstein. 1983. The passive solar construction handbook: featuring hundreds of construction details and notes, materials specifications, and design rules of thumb. Rodale Press, Emmaus, PA. 328 p.

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Articles, Fact Sheets, and Web Sites

Solar Greenhouse Designs and Consultation

The Bioshelter at Three Sisters Farm
The bioshelter includes a solar greenhouse, poultry housing, potting room, seed and tool storage, an equipment storage "barn," a kitchen for packing produce, compost bins, a reference library and living spaces. A full report of the bioshelter design costs $8.00. Three Sisters Permaculture Design also offers consultation on solar greenhouse design, construction and management.

The Green Greenhouse
An excellent site, funded partially by the Northeast SARE, provides detailed design blueprints, materials list, construction suggestions, and performance information for a solar greenhouse.

Growing Concerns, Unlimited. Solar Greenhouses
Provides design and construction consulting services for building solar greenhouses and homes. Specializes in subterranean solar heat systems.

Hobby Greenhouse Association
Sells a Directory of Manufacturers: Hobby Greenhouses, Solariums, Sunrooms, and Window Greenhouses for $2.50. Has links to many greenhouse manufacturers' Web pages. A one-year membership to the association costs $15 and includes a subscription to Hobby Greenhouse, a quarterly magazine, and Hobby Greenhouse News, a quarterly newsletter.

> Hobby Greenhouse Association
> 8 Glen Terrace
> Bedford, MA 01730-2048
> 781-275-0377

Passive Solar Greenhouse
Provides consulting services and passive solar greenhouse plans that have passed building codes for New Mexico. Blueprints include lists of materials and where to purchase them.

Solar Components Corporation
Solar greenhouse kits as well as blueprints and materials for "build-your-own" solar greenhouses.

> Solar Components Corporation
> 121 Valley Street
> Manchester, NH 03103
> 603-668-8186

Sundance Supply
Provides information on greenhouse design and installation. Sells materials needed for constructing and maintaining greenhouses.

Sunglo Solar Greenhouses
214 21st Street SE

Auburn, WA 98002
800-647-0606

Free catalog of greenhouse kits available.

Greenhouse Glazing

Giacomelli, Gene A. 1999. Greenhouse coversing systems - User considerations. Greenhouse glazings: Alternatives under the sun. Cook College. Rutgers University. http://AESOP.RUTGERS.EDU/~ccea/publications.html

Giacomelli, G.A., and W.J. Roberts. 1993. Greenhouse covering systems. HortTechnology. Volume 3, no. 1. p. 50-58.

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Meyer, J. 1985. Greenhouse Construction and Covering Materials. ISHS Acta Horticulturae 170. Ordering information at: www.actahort.org/books/170/

Efficient Windows Collaborative

National Festration Council

Greenhouse Curtains

National Greenhouse Manufactures Association. Helpful Hints: Internal and External Greenhouse Curtain Systems (PDF / 125 K)

Agri-tech. Energy Curtain

FAQs—Internal & External Greenhouse Curtain Systems. Griffin Greenhouse and Nursery Supply

National Greenhouse Manufacturers Association

Solar Chimneys

Anon. 1986. Solar chimney for low-cost desert cooling. Popular Science. May. p. 16B-17C.

Abrams, Don. 1984. The latest on solar chimneys. Rodale's New Shelter. August. p. 10-11.

Abrams, Donald W. 1986. Low-Energy Cooling: A Guide to the Practical Application of Passive Cooling and Cooling Energy Conservation Measures. Van Nostrand Reinhold Co., New York, NY. p. 126-131, 150-161.

Burton, John, and Jeff Reiss. 1981. Project: A solar chimney. p. 623-627. In: Joe Carter (ed.) Solarizing Your Present Home. Rodale Press, Emmaus, PA.

Cunningham, W.A., and T.L. Thompson. 1988. Passive greenhouse cooling. Greenhouse Grower. April. p. 19-20.

Phase-change Materials

Verner, Carl. 1997. Phase Change Thermal Energy Storage.

http://freespace.virgin.net/m.eckert/carl_vener's_dissertation.htm

General Greenhouse Information

Abraham, Doc and Katy. 1993. What to look for in a greenhouse. Consumers' Research. January. p. 31-35.

Good introduction to greenhouses in general.

Dickerson, Lizzy. 1992. The stone-built, bermed greenhouse. Maine Organic Farmer & Gardener. May-June. p. 16-17.

Hofstetter, Bob. 1989. Tunnels of plenty. The New Farm. November-December. p. 36-39.

Hofstetter, Bob. 1990. The New Farm's greenhouse guide. The New Farm. September-October. p. 32-36.

von Zabeltitz, Christian. 1990. Greenhouse construction in function of better climate control. Acta Horticulturae Vol. 263. p. 357-366

Greenhouse Technical and Trade Publications

Acta Horticulturae
Journal of the International Society for Horticultural Science
ISHS Secretariat
P.O. Box 500
3001 Leuven 1, Belgium

Greenhouse Grower
Meister Publishing Company
37733 Euclid Ave.
Willoughby, OH 44094
216-942-2000

GM Pro (formerly Greenhouse Manager)
Branch-Smith Publishing
120 St. Louis Ave.
Fort Worth, TX 76101
800-433-5612
817-882-4121 FAX
www.greenbeam.com

NM Pro (formerly Nursery Manager)
Branch-Smith Publishing
120 St. Louis Ave.
Fort Worth, TX 76101
800-433-5612
817-882-4121 FAX
www.greenbeam.com

GrowerTalks
Ball Publishing
335 N. River Street
PO Box 9
Batavia, IL 60510-0009 USA
630-208-9080
630-208-9350 FAX

Greenhouse Product News
Scranton Gillette Communications, Inc.
380 E. Northwest Hwy.
Des Plaines, IL 60016-2282
708-290-6622

Solar Energy Organizations: National

American Solar Energy Society
2400 Central Ave., G-1
Boulder, CO 80301
303-443-3130

> Publishes Solar Today magazine and an annual membership directory; $70 annual membership fee.

National Renewable Energy Laboratory. Energy Efficiency and Renewable Energy. U.S. Department of Energy. Passive Solar Heating, Cooling and Daylighting.
www.eere.energy.gov/de/cs_passive_solar.html

> **Fact sheets include:**
> Sunspace Basics
> Passive Solar Design for the Home
> Phase Change Materials for Solar Heat Storage
> Phase Change Drywall
> Trombe Walls

U.S. Department of Energy. Office of Building /Technology, State and Community Programs. Publications.

> **Fact sheets include:**
> Passive Solar Design
> The Solar Energy Research Facility

Renewable Energy Policy Project and Center for Renewable Energy and Sustainable Technology
Links to national, state, and international solar energy associations.

Database of State Incentives for Renewable Energy (DSIRE)
Links to state, local, utility, and selected federal incentives that promote renewable energy.

Solar Energy Organizations: State

Illinois Solar Energy Association

> **Fact sheets include:**
> Passive Solar Energy I and II
> Solar Thermal Heat
> Solar Greenhouse

Indiana: Purdue University Cooperative Extension Service

> **Fact sheet:**
> Solar Energy Heat Storage for Home, Farm and Small Business: Suggestions on Selecting and Using Thermal Storage Materials and Facilities

New Mexico Solar Energy Association

Fact sheets include:
Passive Solar Design Guidelines for Northern New Mexico
Passive Solar Design Primer

North Carolina Solar Center. Energy Division North Carolina Department of Commerce

Fact sheets include:
Passive Solar Design Checklist
Sunspace Design Basics
Passive Solar Retrofit for North Carolina Homes

Oklahoma State Cooperative Extension Service

Fact sheets include:
Greenhouse Structures and Coverings (PDF / 35 K)
Locating the Greenhouse (PDF / 43 K)

Solar Energy Association of Oregon

Fact sheets include:
Passive Solar Design
Passive Solar Energy Lesson Plans for elementary students

Texas State Energy Conservation Office
and
Texas Solar Energy Society

Fact sheets include:
Passive Solar Design for the Home
Solar Water Heaters

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Computer Software

EREC. n. d. Computer Software for Solar Energy Analysis and System Design. EREC Reference Briefs. U.S. Department of Energy. Office of Energy Efficiency and Renewable Energy. www.eere.energy.gov/buildings/tools_directory/software.cfm/ID=88/

Energy-10. A software package for solar energy design. Available from Solar Building Industries Council. www.sbicouncil.org/store/index.php

SUN_CHART™. A computer software that calculates and screen plots both cylindrical and polar suncharts for any desired latitude. Available from:

Optical Physics Technologies
P.O. Box 11276
Tucson, AZ 85734

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